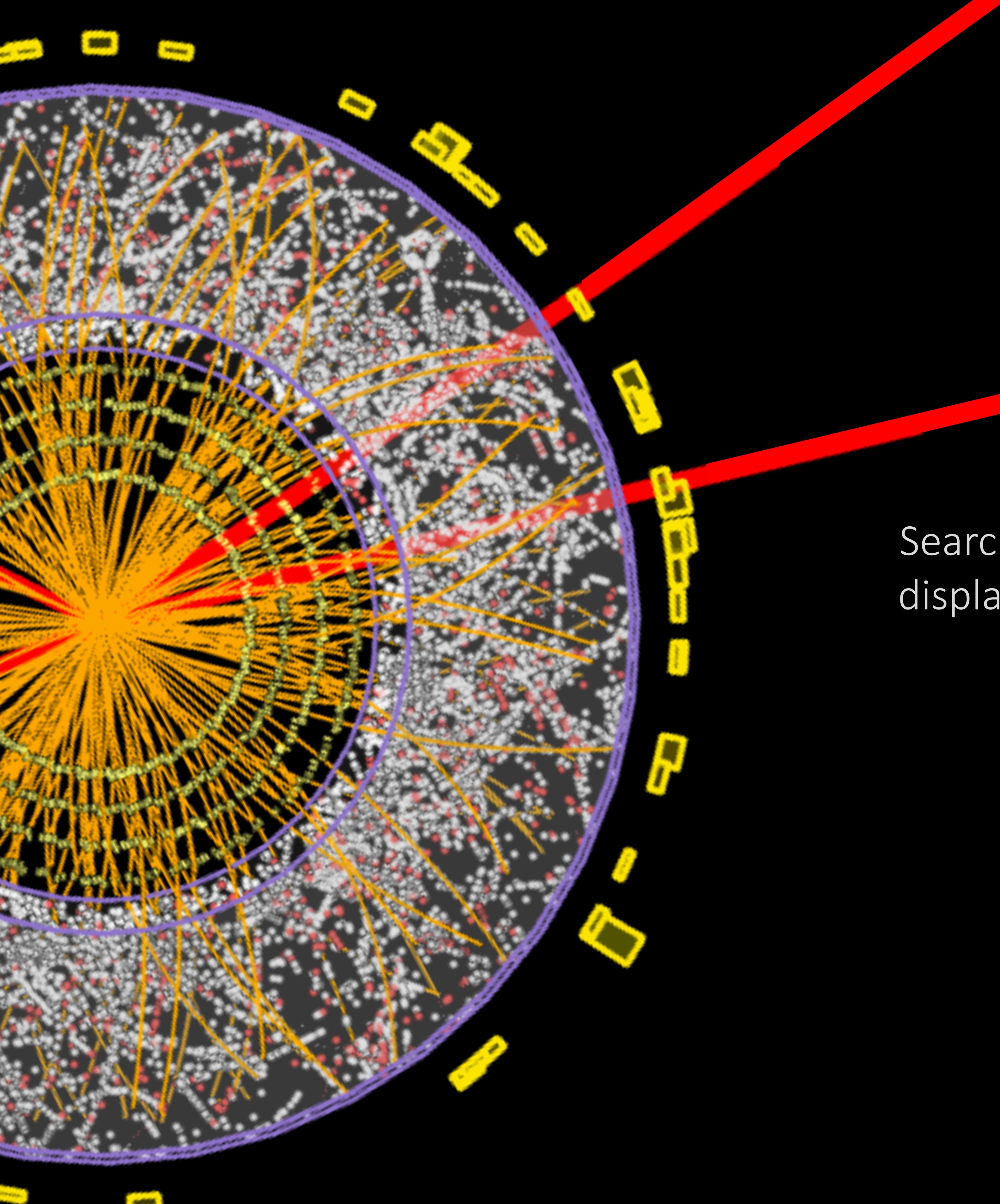


Searching for long-lived particles with displaced vertices in ATLAS at the LHC

featuring the Muon Spectrometer

Karri Folan DiPetrillo
Harvard University
6 Dec 2018

ATLAS EXPERIMENT

Searching for long-lived particles (LLPs)

in events with a displaced vertex (DV) and a muon in the ATLAS detector using pp-collisions from Run 2 of the LHC

ATLAS Run 1 Displaced Vertex + Muon — ATLAS-SUSY-2014-02
CMS Run 2 Displaced Jets 35.9 fb^{-1} —CERN-EP-2018-289
CMS Run 2 Displaced Leptons 2.6 fb^{-1} — CMS-PAS-EXO-16-022

Beyond Standard Model physics searches at the LHC

We know Standard Model isn't full picture of the universe

but no signs of beyond Standard Model physics so far at the LHC
especially in obvious channels

	Run 1 2010-2012	Run 2 2015-2018	Run 3 2021-2023	HL-LHC 2026-
$\sqrt{s}$	7-8 TeV	13 TeV	14 TeV	14 TeV
Integrated Luminosity	26 fb^{-1}	140 fb^{-1}	150 fb^{-1}	3000 fb^{-1}

increases in energy (Run 1 – Run 2) | increases in dataset size (Run 3 – HL-LHC)

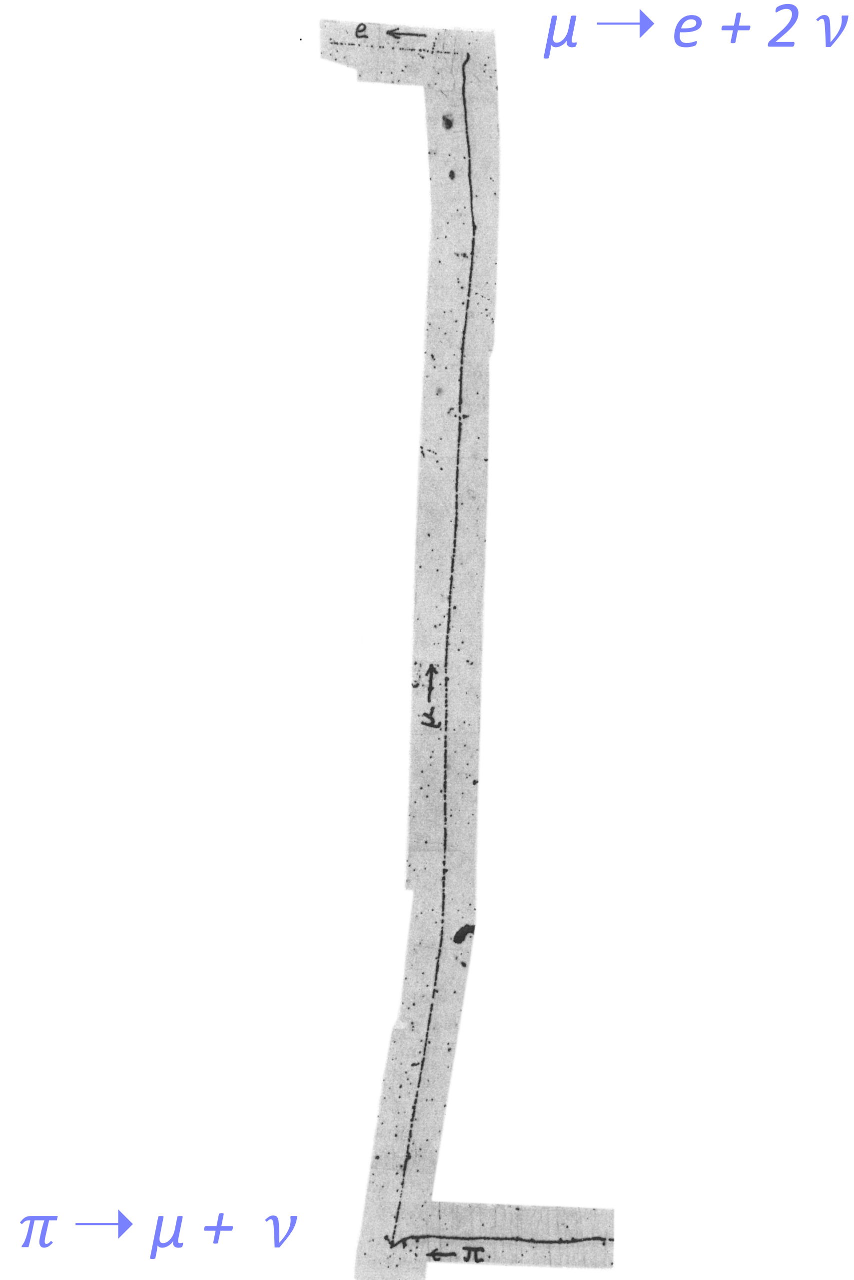
Important that we consider models with
challenging final states

Looking for long-lived particles

well motivated from physics perspective
and also exciting from an experimental perspective

Why long-lived particles

Standard Model already full of long-lived particles



(1949) *Nature* **163**, 82.

Why long-lived particles

Standard Model already full of long-lived particles

small couplings

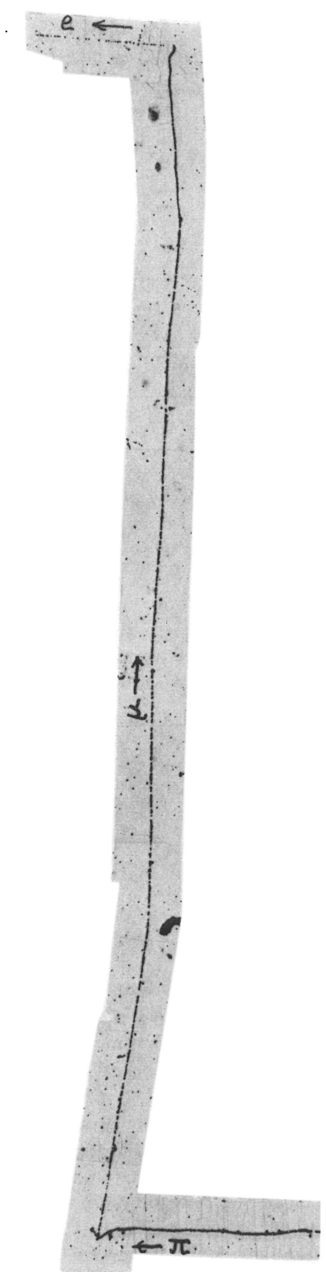
b-mesons, off-diagonal CKM, $\tau \approx$ ps

high mass mediator

μ, π, via W, $\tau \approx 2$ μs, 26 ns

small mass splittings

neutron, $m_n - m_p \approx 1$ MeV, $\tau = 15$ min



(1949) *Nature* **163**, 82.

Why long-lived particles

Standard Model already full of long-lived particles

These same mechanisms come into play with new physics

small couplings

b-mesons, off-diagonal CKM, $\tau \approx$ ps

high mass mediator

μ, π, via W, $\tau \approx 2\ \mu s$, 26 ns

small mass splittings

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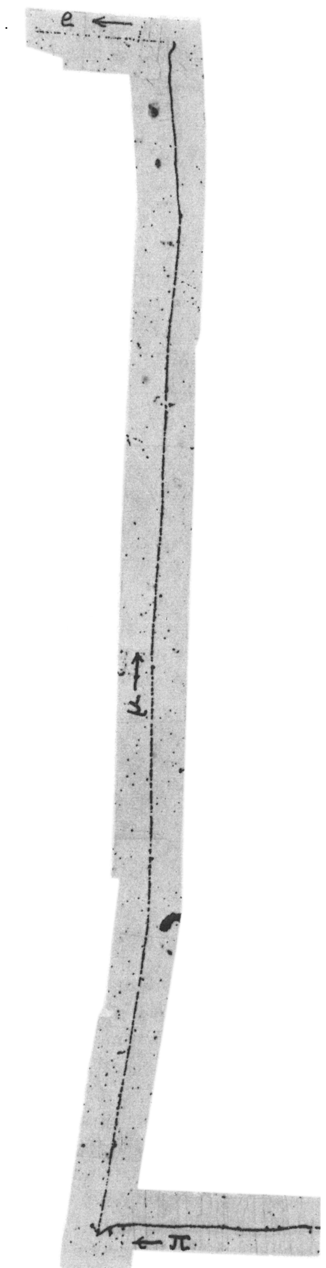


(1949) *Nature* **163**, 82.

Supersymmetry

Hidden Sectors

Dark Matter

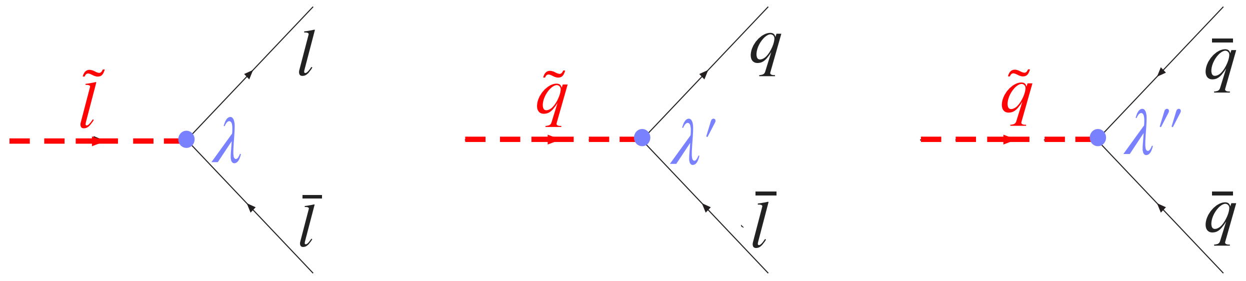
etc

R-parity Violating Supersymmetry

SUSY: rough idea, new relationship between fermions and bosons, fundamental Standard Model particles get a super partner

R-parity Violation: if we write down SUSY in most generic form we get the following lepton & baryon number violating couplings

$$W_{\Delta B,L} = \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \lambda''_{ijk} U_i D_j D_k + \kappa_i L_i H_u$$



L,E = leptons
Q,D,E = quarks
H=Higgs

The only way lightest SUSY particle can decay is to Standard Model particles via R-parity Violating couplings

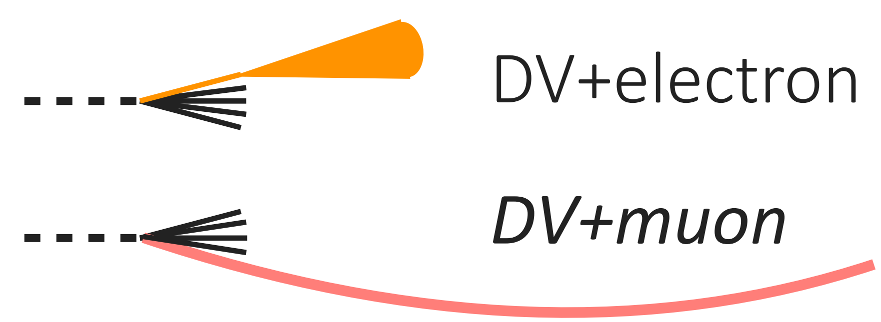
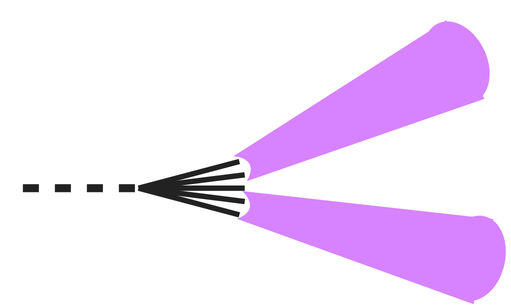
we think couplings are likely small → ps-ns lifetimes → displaced vertices

R-parity = +1 for regular particles
R-parity = -1 for superpartners

How do we probe these couplings?

ATLAS has several analyses looking for displaced vertices

DV+muon uniquely sensitive to λ'_{2jk}

Coupling	Physics Signature	Example Detector Signature
λ_{ijk}	leptonic LLP decays ee,μμ,μe,…	 di-lepton DV
λ'_{1jk} λ'_{2jk}	semi-leptonic LLP decays lq,lqq	 DV+electron *DV+muon*
λ''_{ijk}	hadronic LLP decays qq,qqq	 DV+jets

DV+muon Interpretation

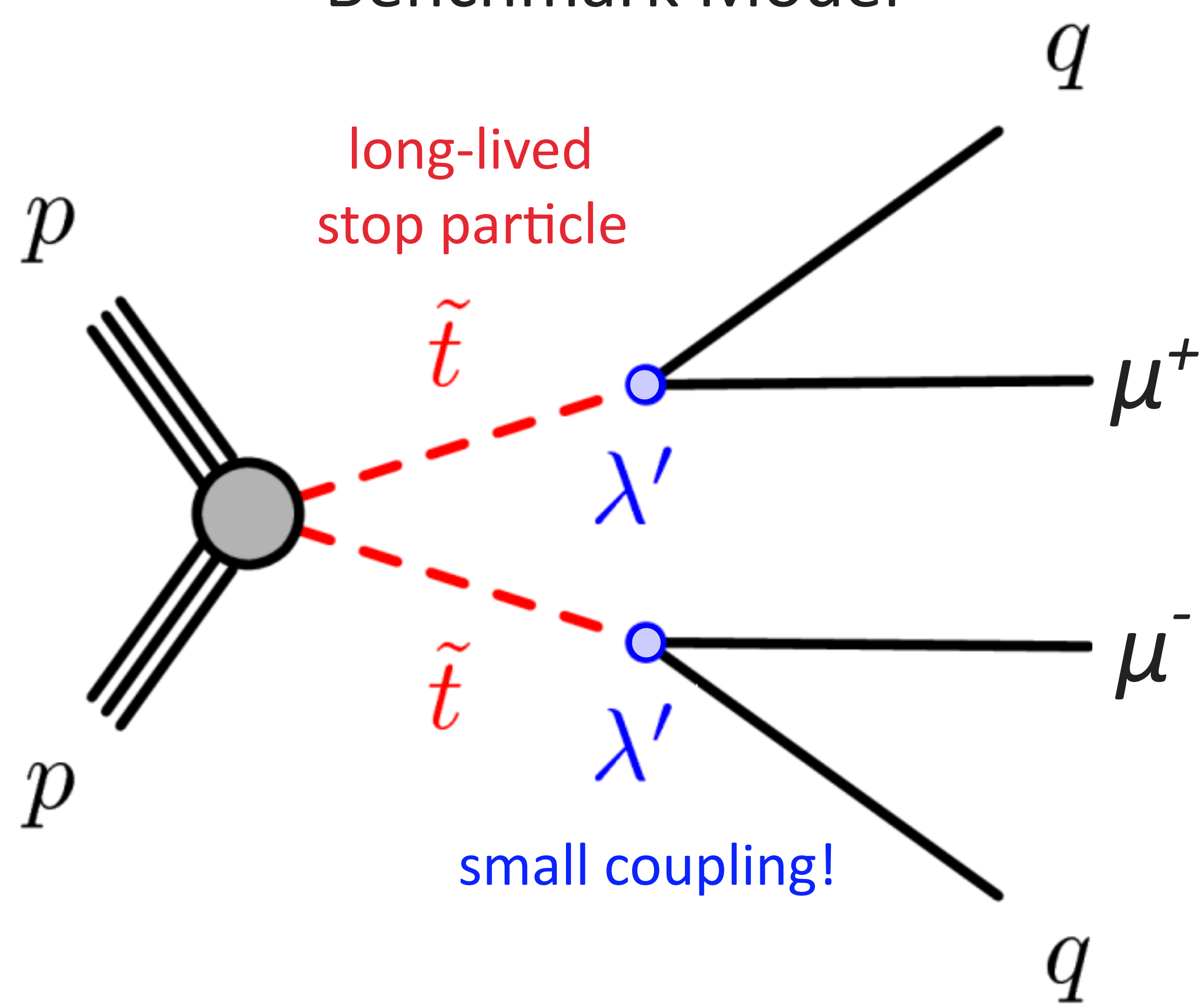
Goal: probing λ'_{2jk}

As a benchmark, consider
pair production of stop particles

stop = top quark partner
lightest SUSY particle
and long-lived

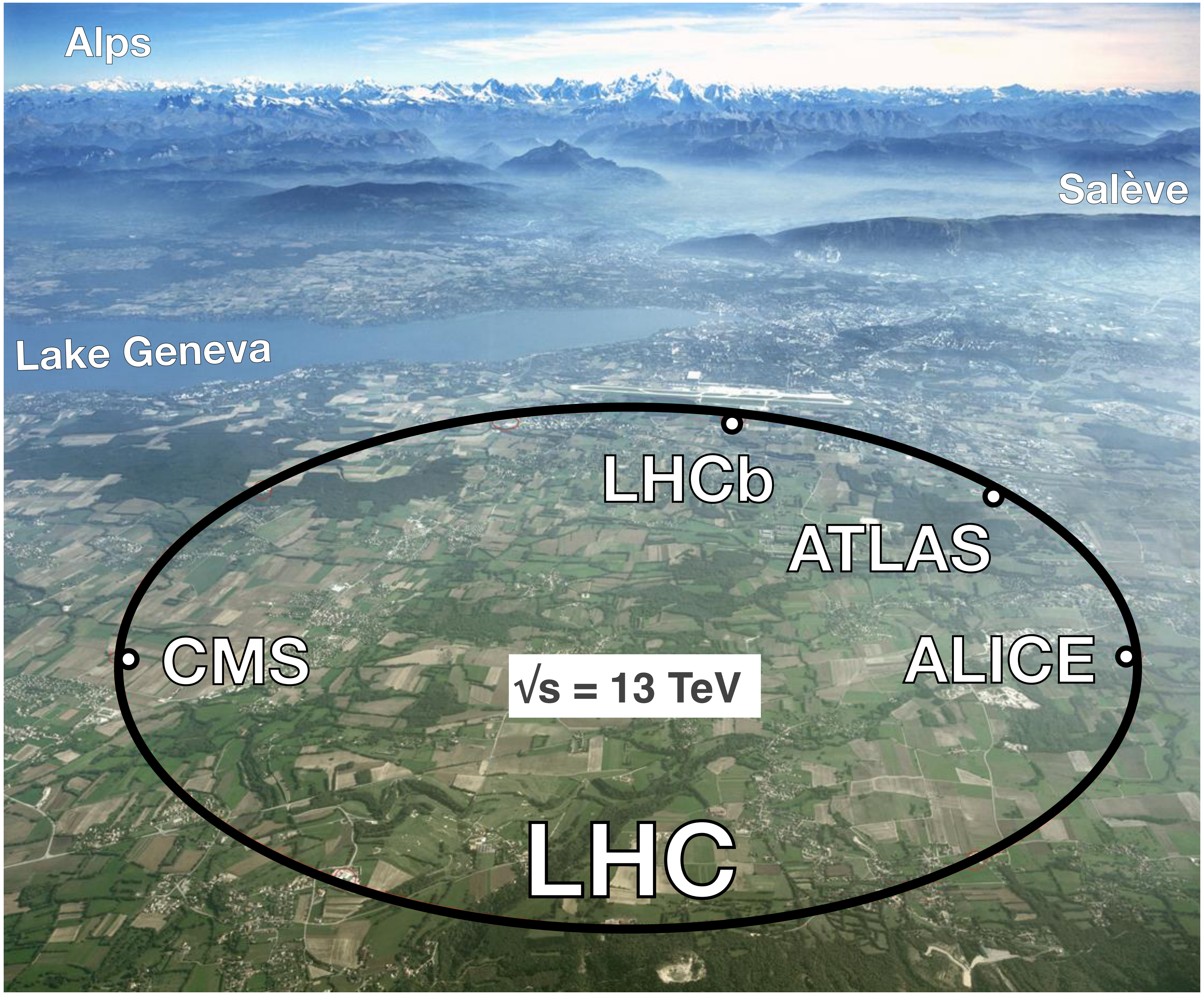
stop decays to a jet and a muon
via a small λ' coupling

Benchmark Model



Note: stop hadronizes with Standard Model particles to form a color singlet state → R-hadron

The Large Hadron Collider



our analysis using 137 fb^{-1} of pp-collisions from 2016-2018
this talk uses preliminary results with 77.3 fb^{-1} from 2016-2017

ATLAS Detector Design

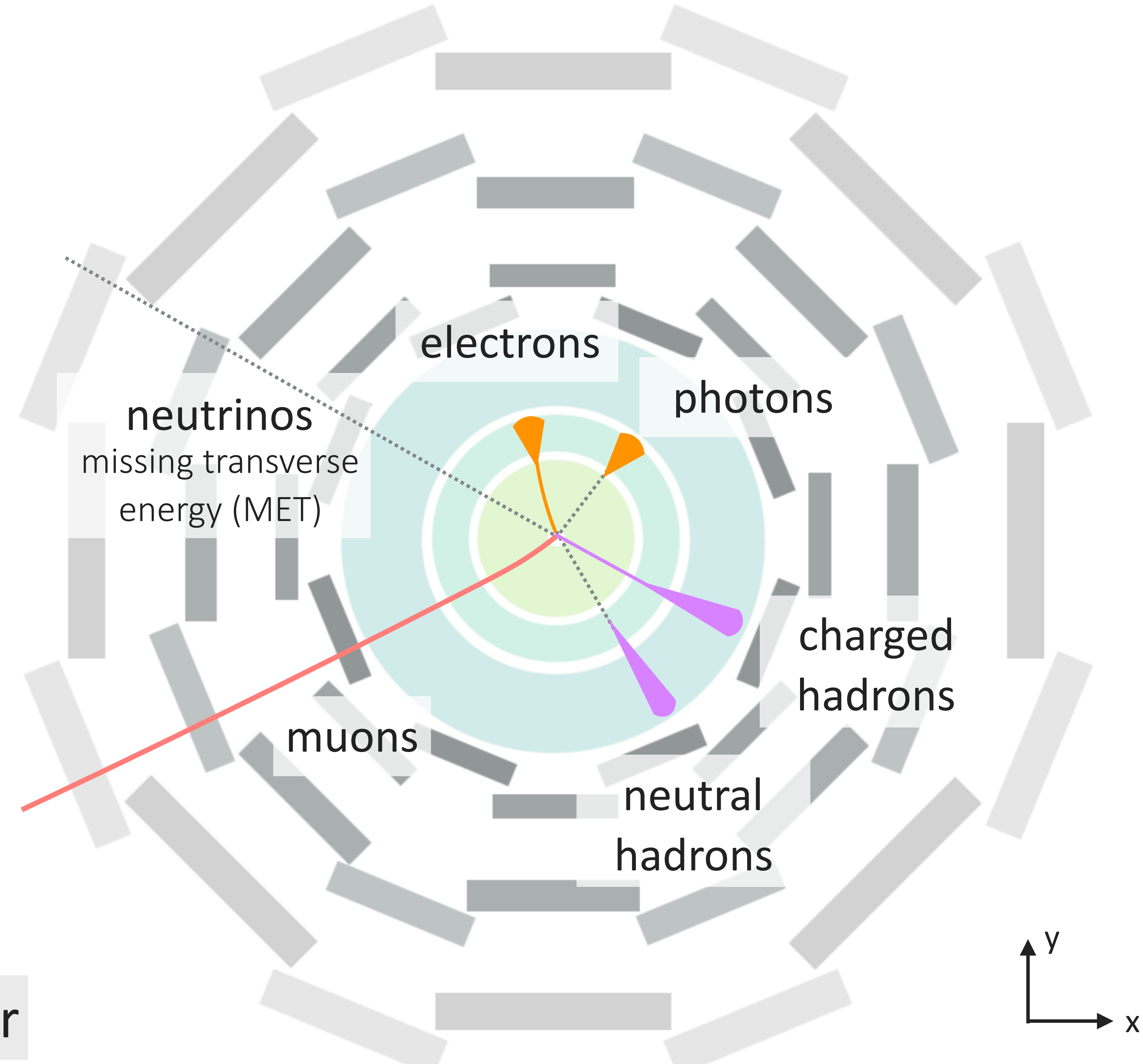
4π coverage
cylindrical geometry
barrel + endcaps

Inner Detector

Electromagnetic Calorimeter

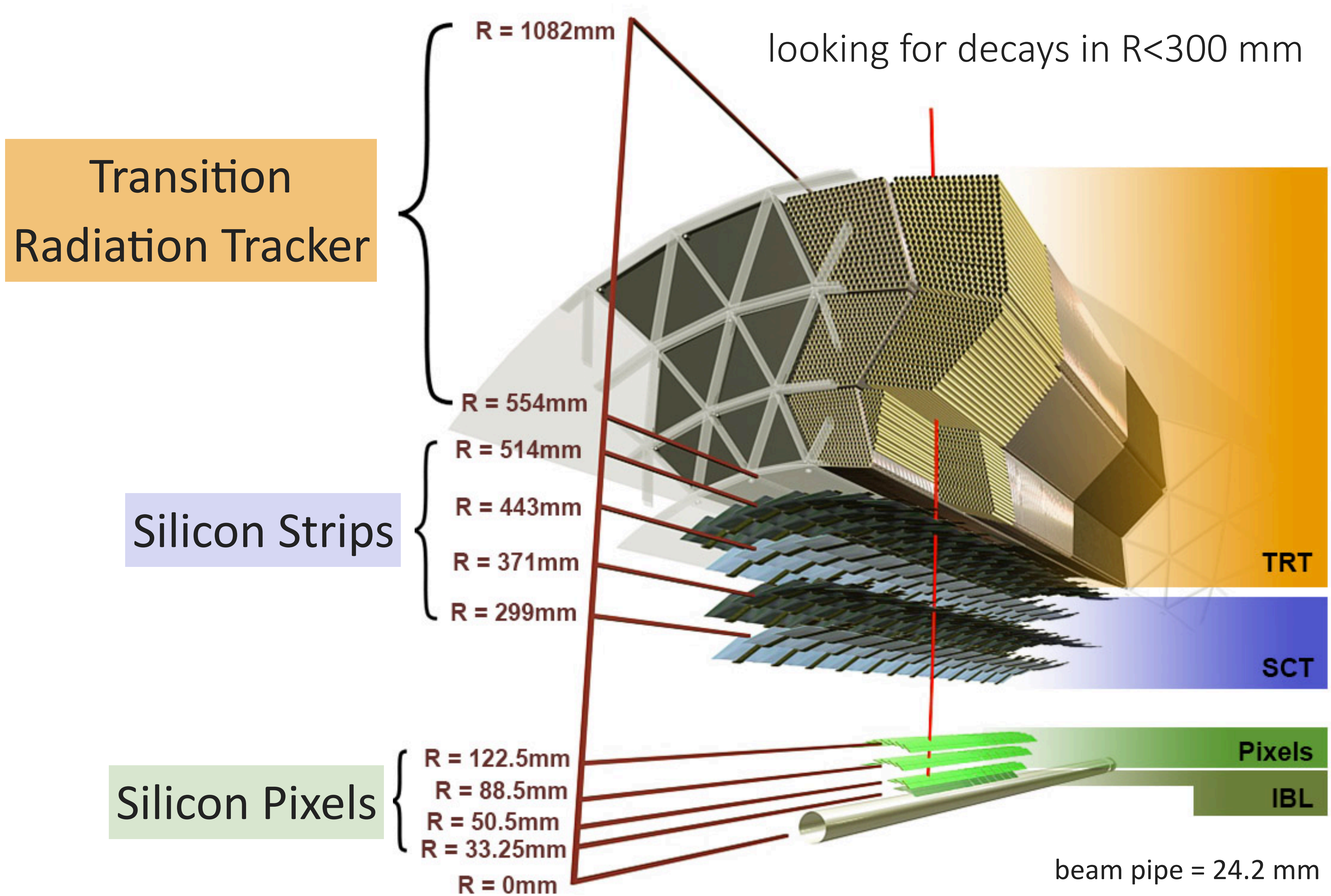
Hadronic Calorimeter

Muon Spectrometer



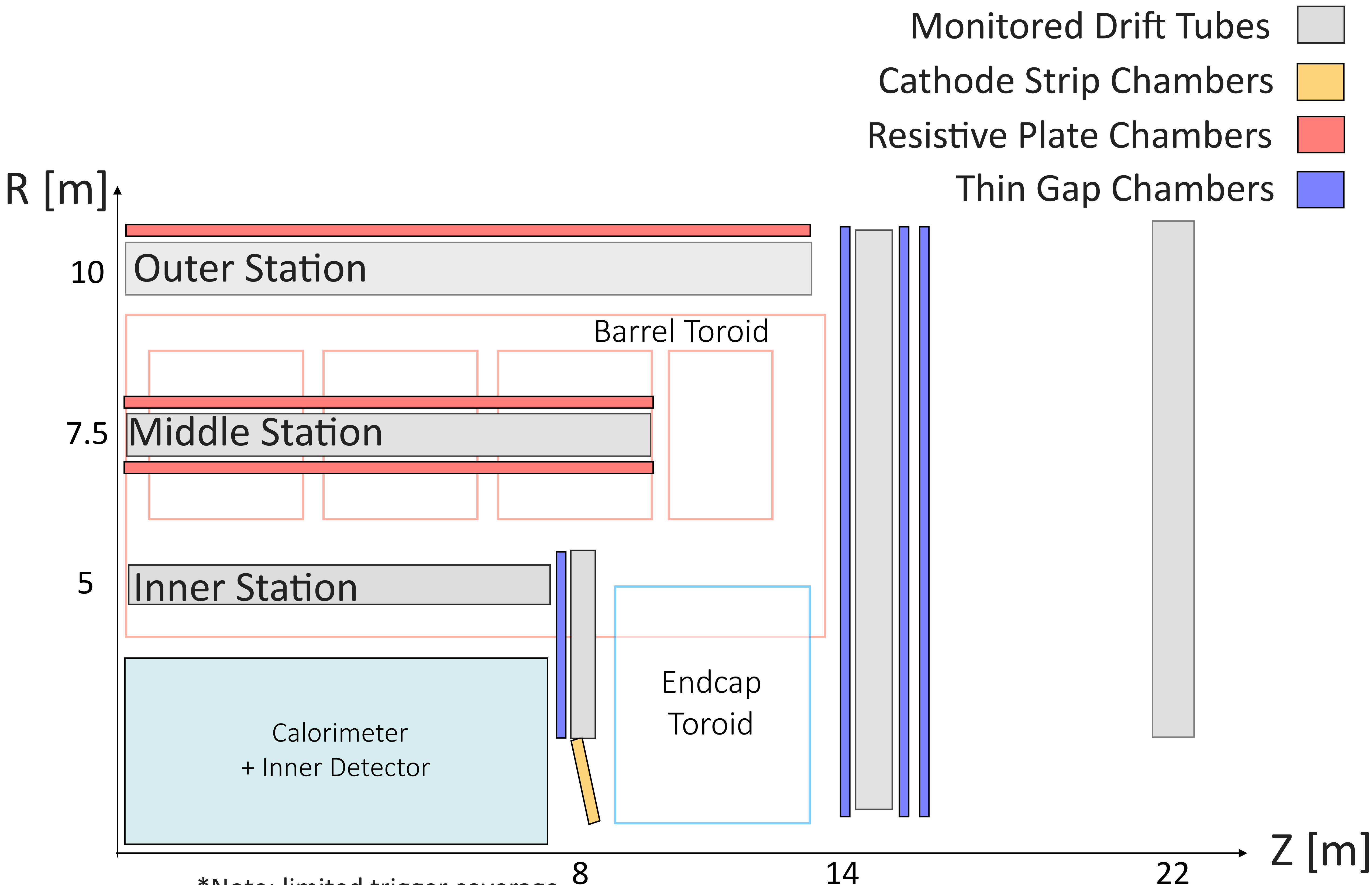
Inner Detector

looking for decays in R<300 mm



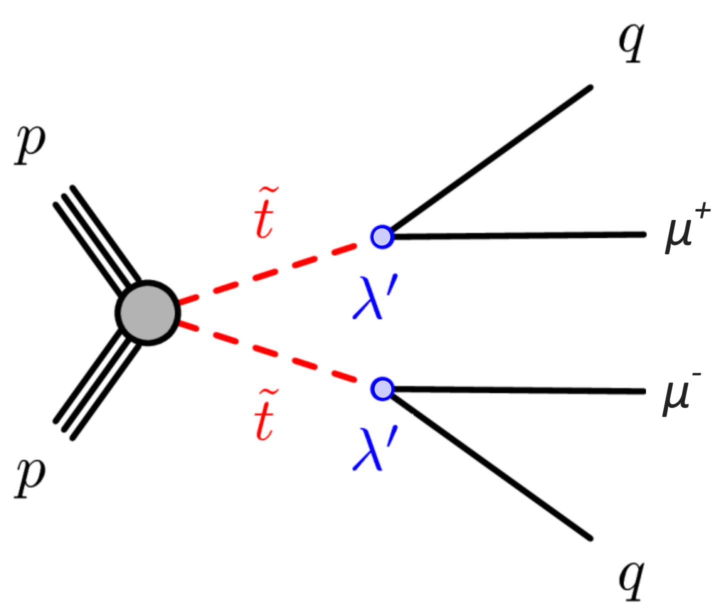
beam pipe = 24.2 mm

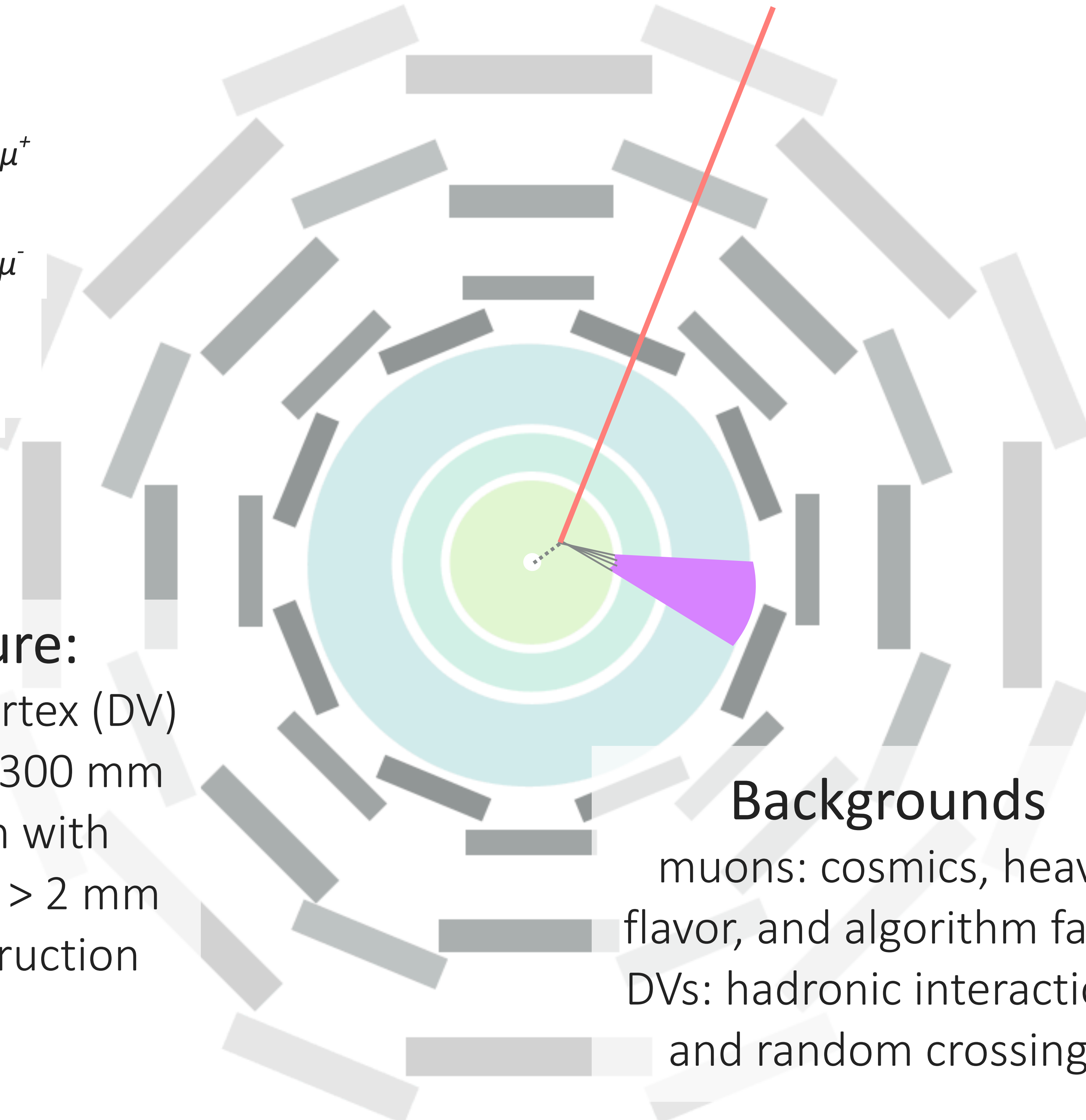
Muon Spectrometer



*Note: limited trigger coverage in the Inner Endcap

DV+muon in the ATLAS Detector





Detector Signature:

at least one Displaced Vertex (DV) in R<300 mm and |Z| < 300 mm and a displaced muon with impact parameter, |d0| > 2 mm

*non-standard reconstruction

Backgrounds

muons: cosmics, heavy flavor, and algorithm fakes

DVs: hadronic interactions and random crossings

DV+muon Analysis Strategy

In general

use stop → μ + jet as a benchmark

but remain open minded to other signals

eg. neutral LLP → μ + 2 jets, cascade decays, etc

We know from previous versions of the analysis

we can have ~0 expected background

and retain excellent signal efficiency

Define two levels of selection for vertices and muons

1. preselection - loose, lets us study backgrounds
2. full selection - tight, strong background rejection

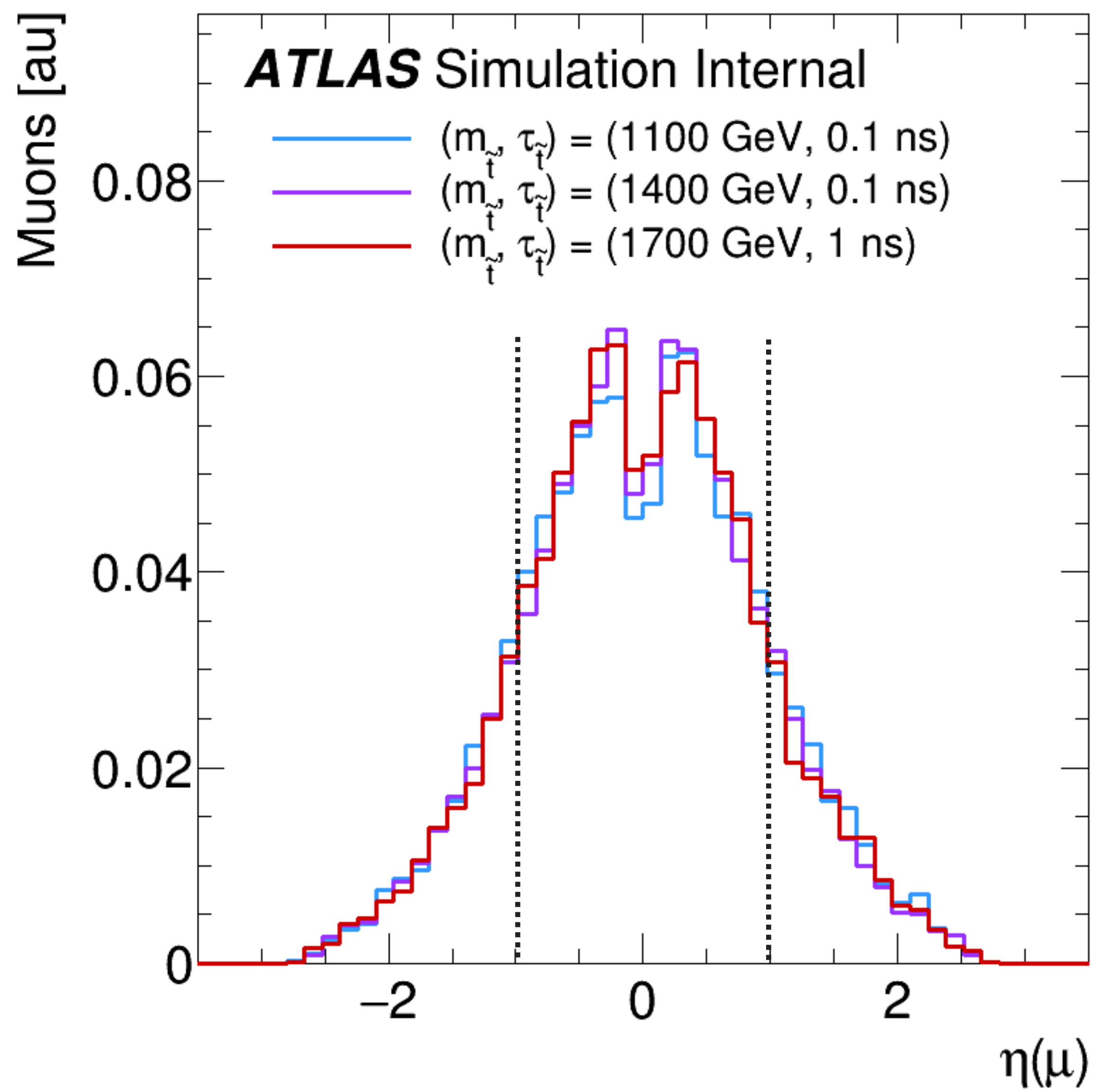
Trigger Strategy

in Run 1: Muon Spectrometer Only Trigger

requires Muon Track only - agnostic to Inner Detector activity
compare this to Standard Muon Triggers, |d0| < 10 mm
challenge: large background rate in endcaps, only use barrel

Trigger acceptance
defined by
$|\eta| < 1.05$
and pT > 62 GeV

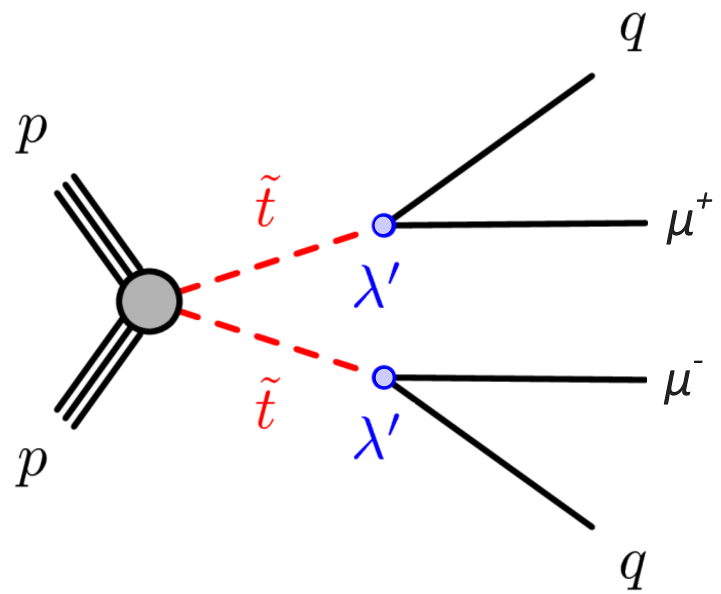
Trigger Efficiency
defined by
trigger detector coverage
Level 1 pointing assumptions



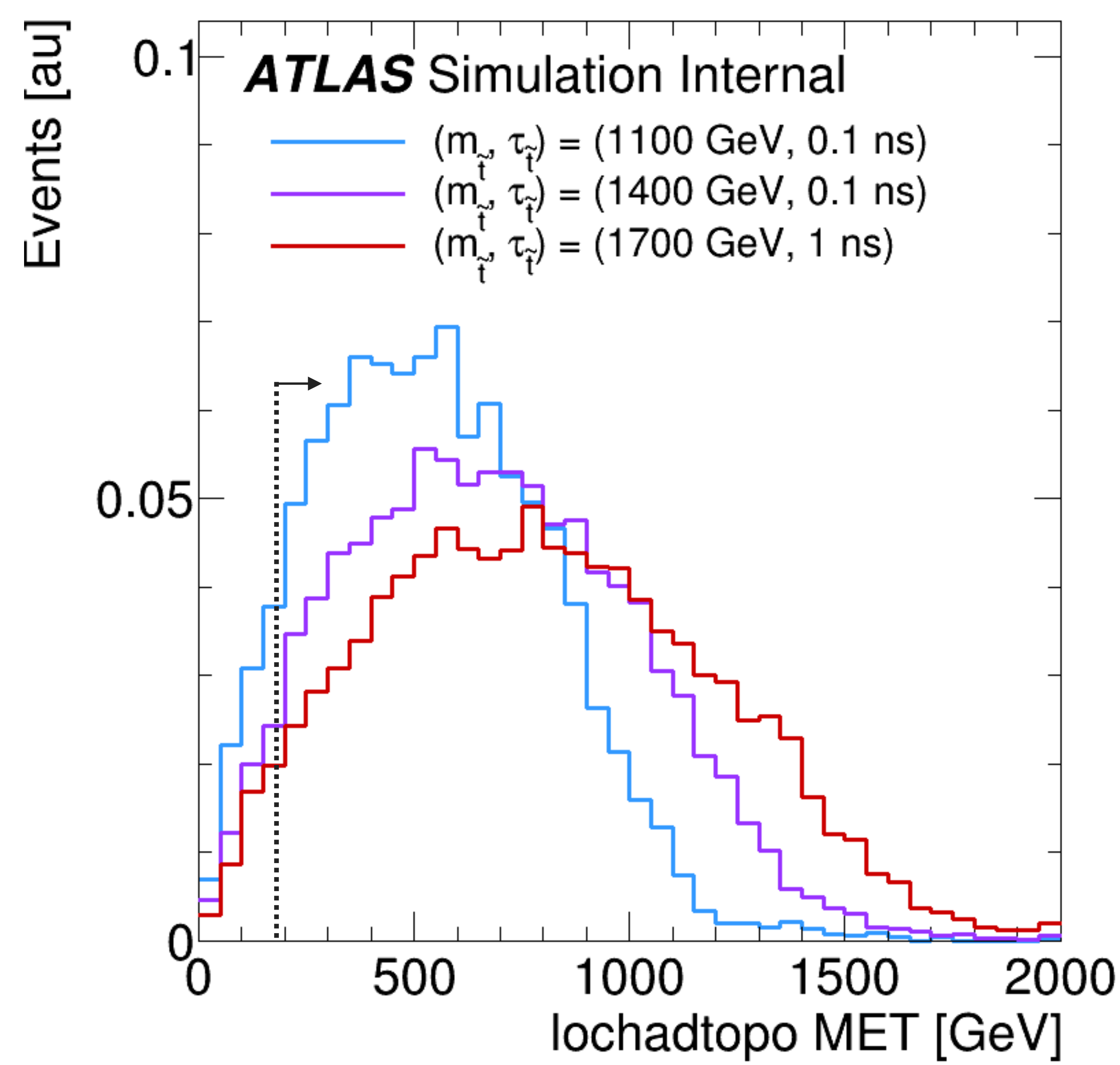
Trigger Strategy

New idea: use a Missing Transverse Energy (MET) Trigger

muons ~invisible to calorimeter



Trigger is 100% efficient when calorimeter-based Missing Transverse Energy > 180 GeV



lochadtopo MET = cluster based calorimeter MET

Trigger Strategy

Strategy in Run 2

MET Stream: MET Trigger if calorimeter MET > 180 GeV
Muon Stream: Muon Trigger if calorimeter MET < 180 GeV

MET trigger most efficient for our model
keep Muon trigger for completeness

new strategy improves overall signal acceptance x efficiency for our benchmark model by > 40% with respect to Run 1

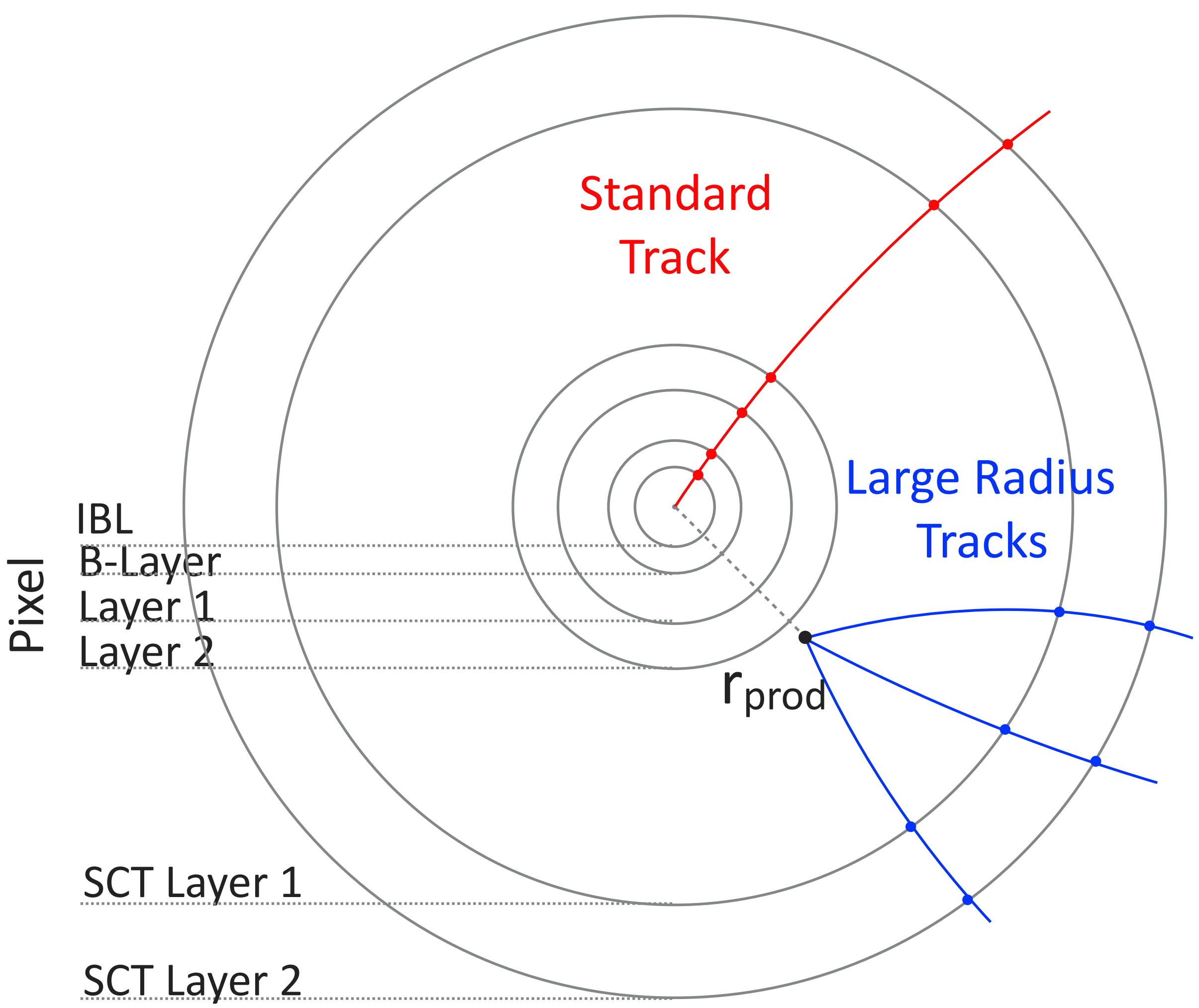
Non-Standard Reconstruction

Inner Detector Tracking

standard tracking requires |d0| < 10 mm

large radius tracking is an additional pass of tracking with loosened impact parameter and hit requirements

challenge for this analysis: fake tracks



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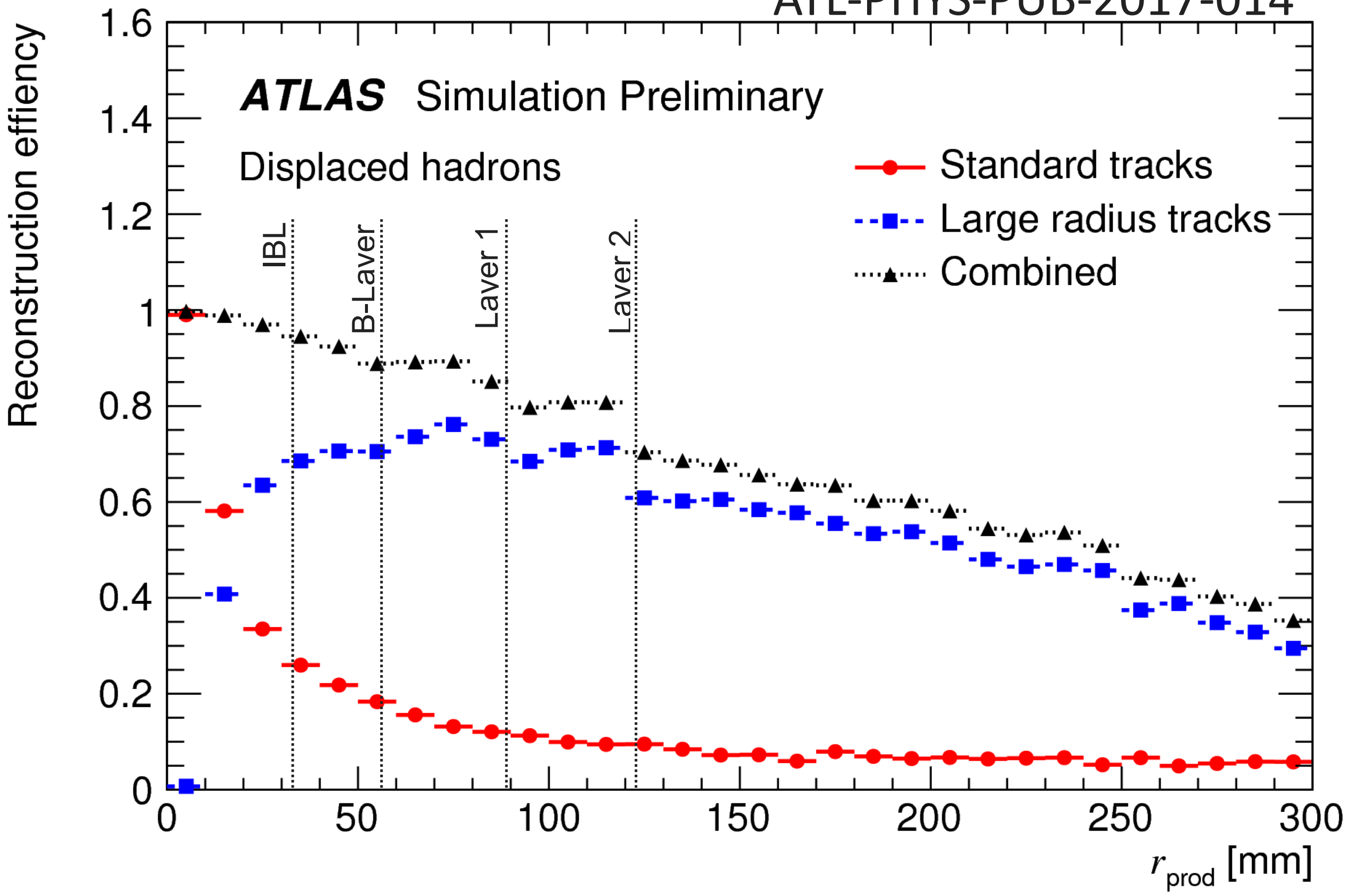


Non-Standard Reconstruction

Secondary Vertexing

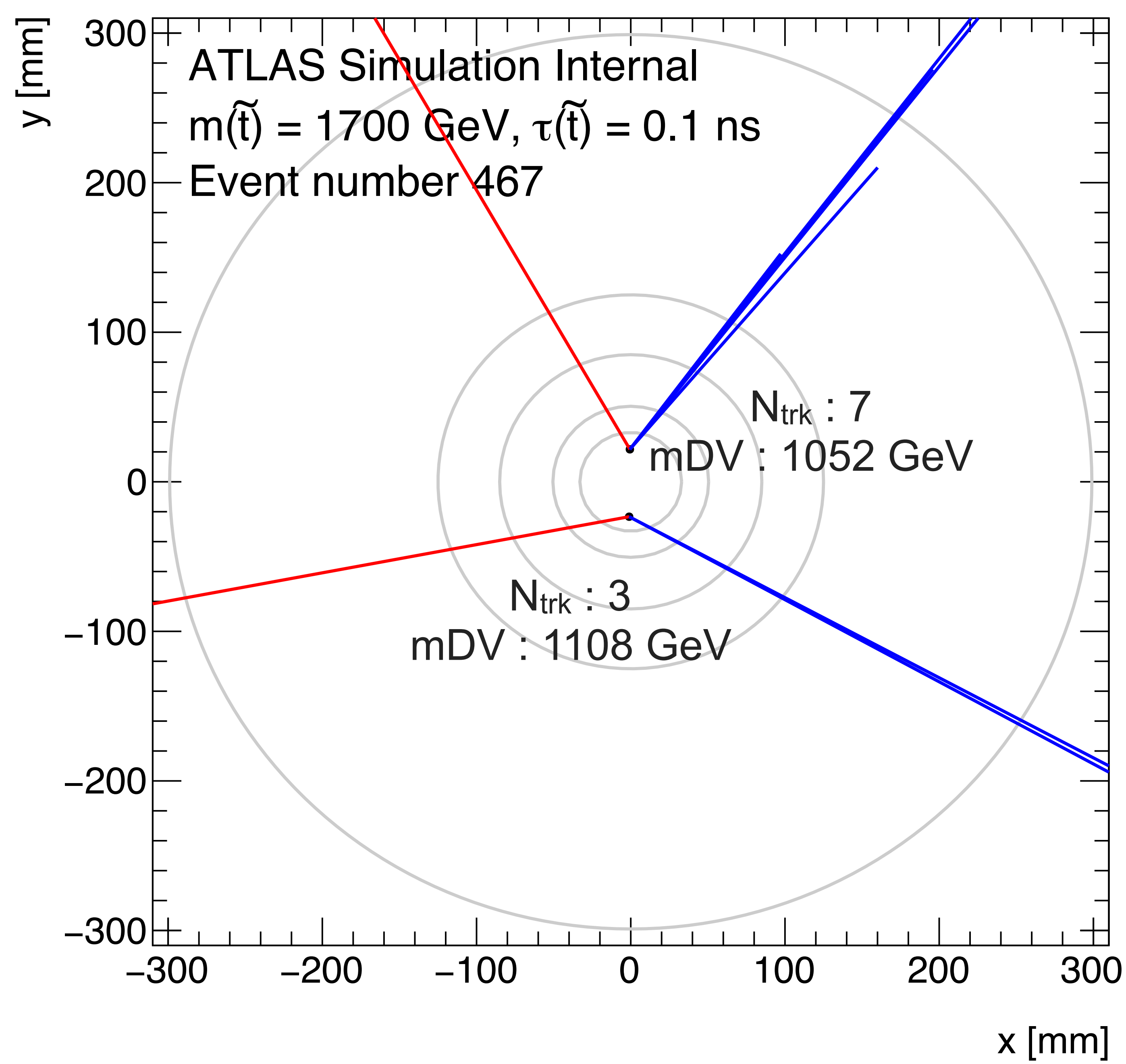
forms vertices using tracks with
pT > 1 GeV and |d0| > 2 mm
Rxy < 300 mm
|Z| < 300 mm

Signal Event Display

with **muons** and **tracks**
associated to displaced vertices

Challenge:

vertexing efficiency losses
at large radii

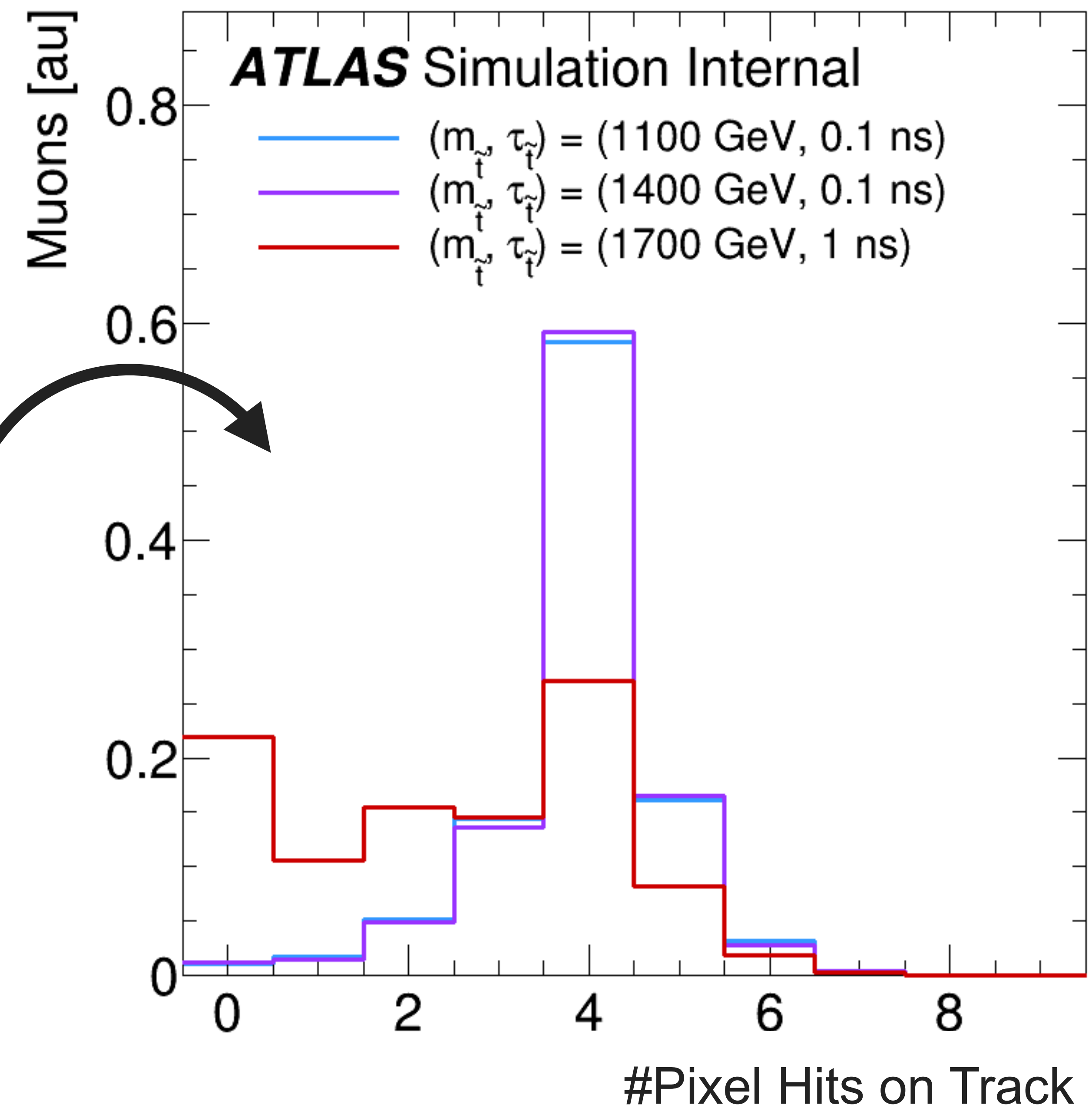


Muon preselection

Preselected muons

combined muon, “medium” quality with relaxed hit requirements

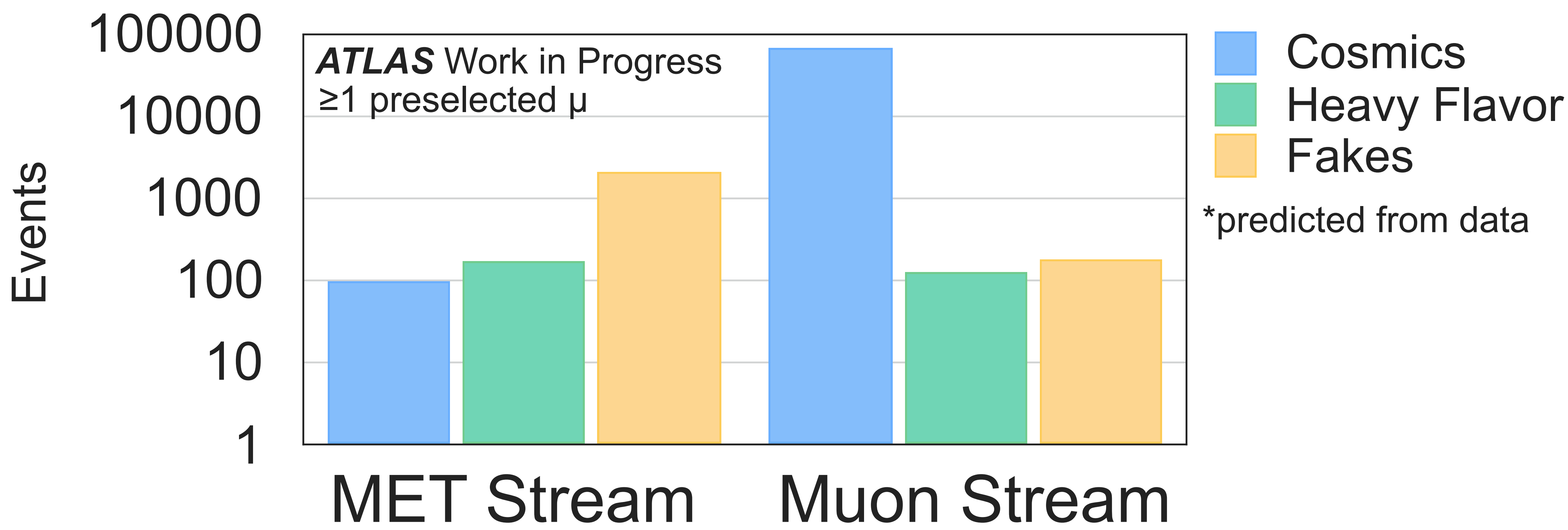
|eta| < 2.5
pT > 25 GeV
|d0| > 2.0 mm



Muon selection

After muon preselection, events in data are dominated by

algorithm fakes, muons from heavy flavor decays, cosmics



→ Design a dedicated veto for each background

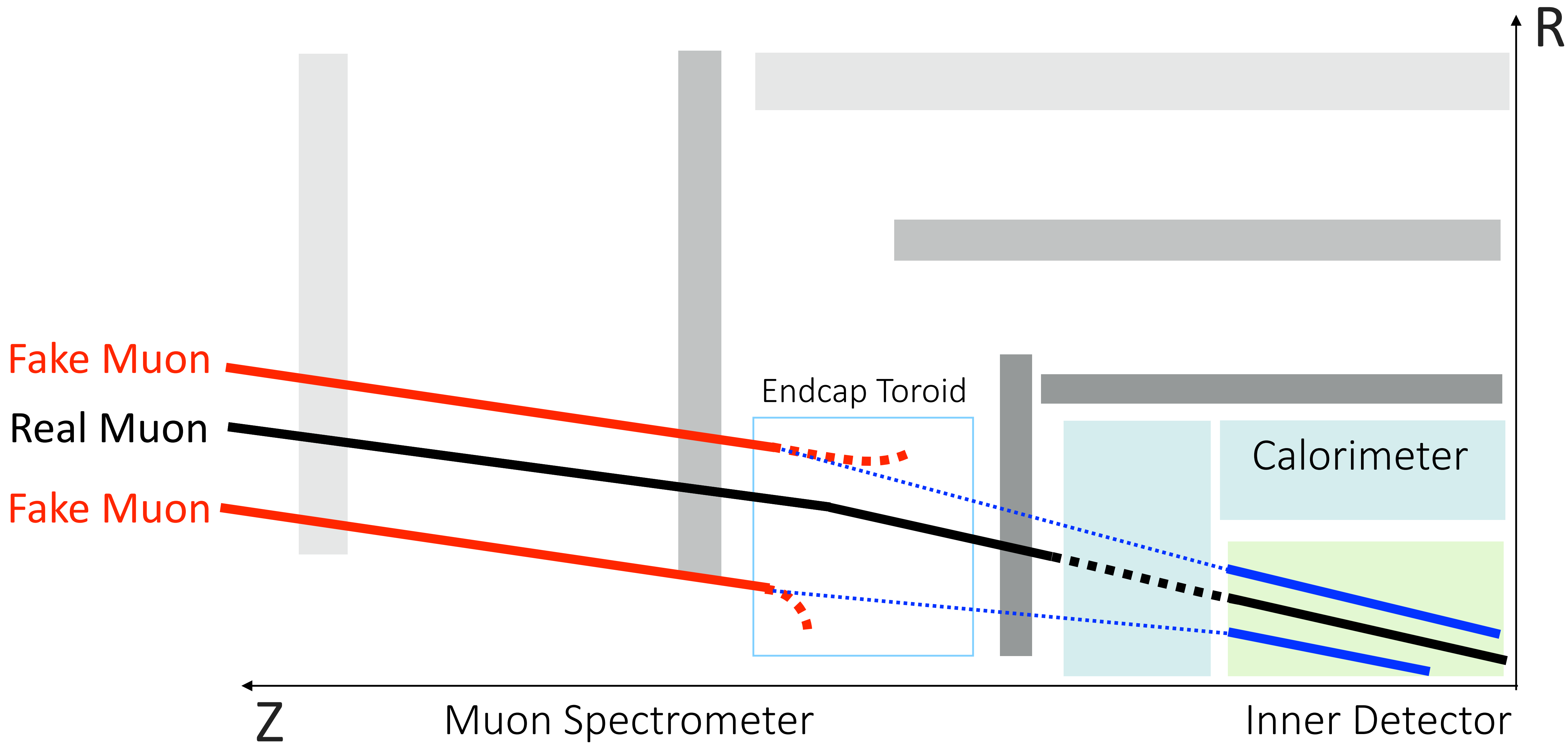
with the idea that inverting each veto gives you
a control region pure in particular background

Algorithm Fakes

Largest background in MET triggered events

mostly in endcaps, a unique background to analyses using large radius tracking

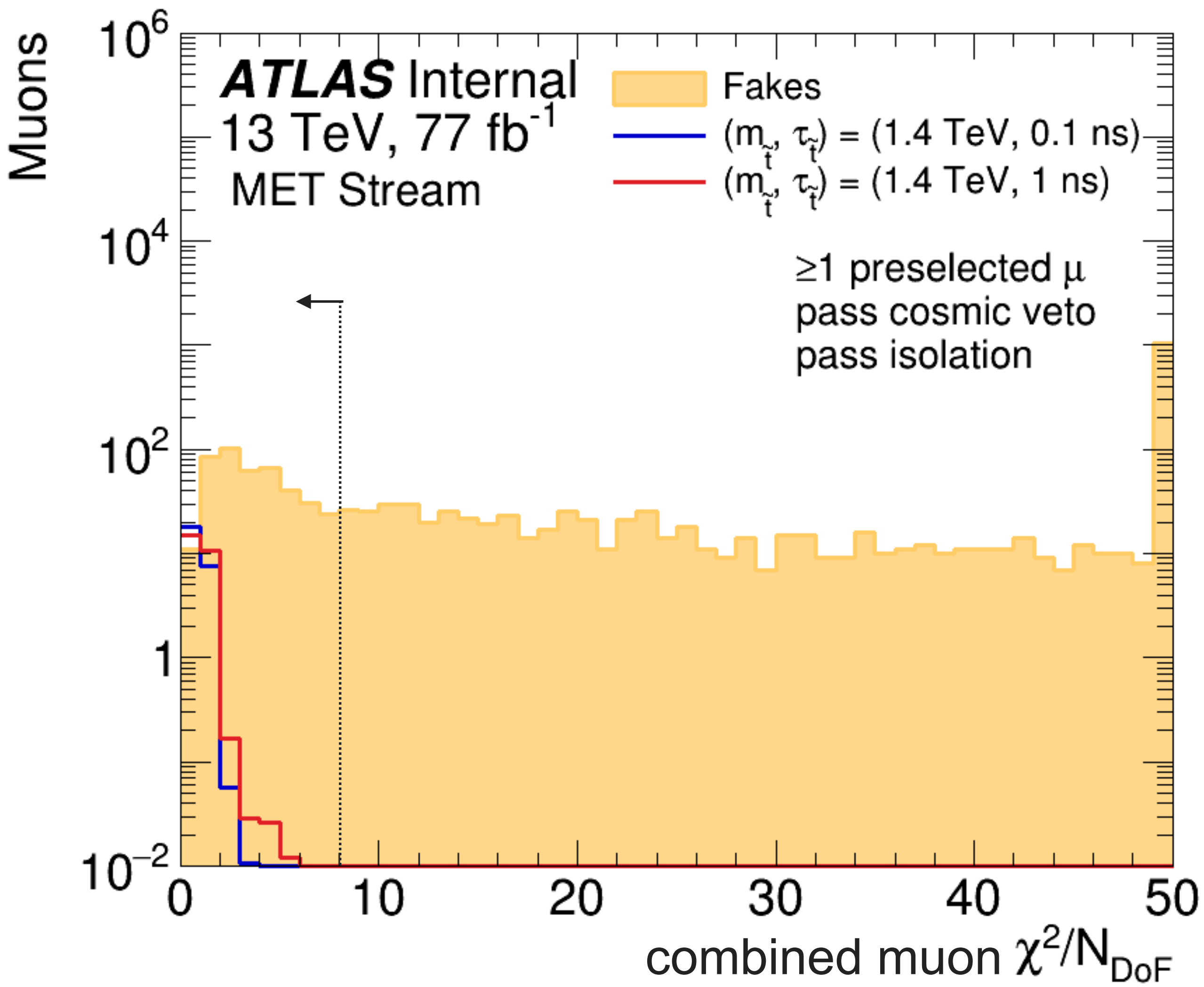
fake **muon spectrometer track** matched to fake **inner detector track**

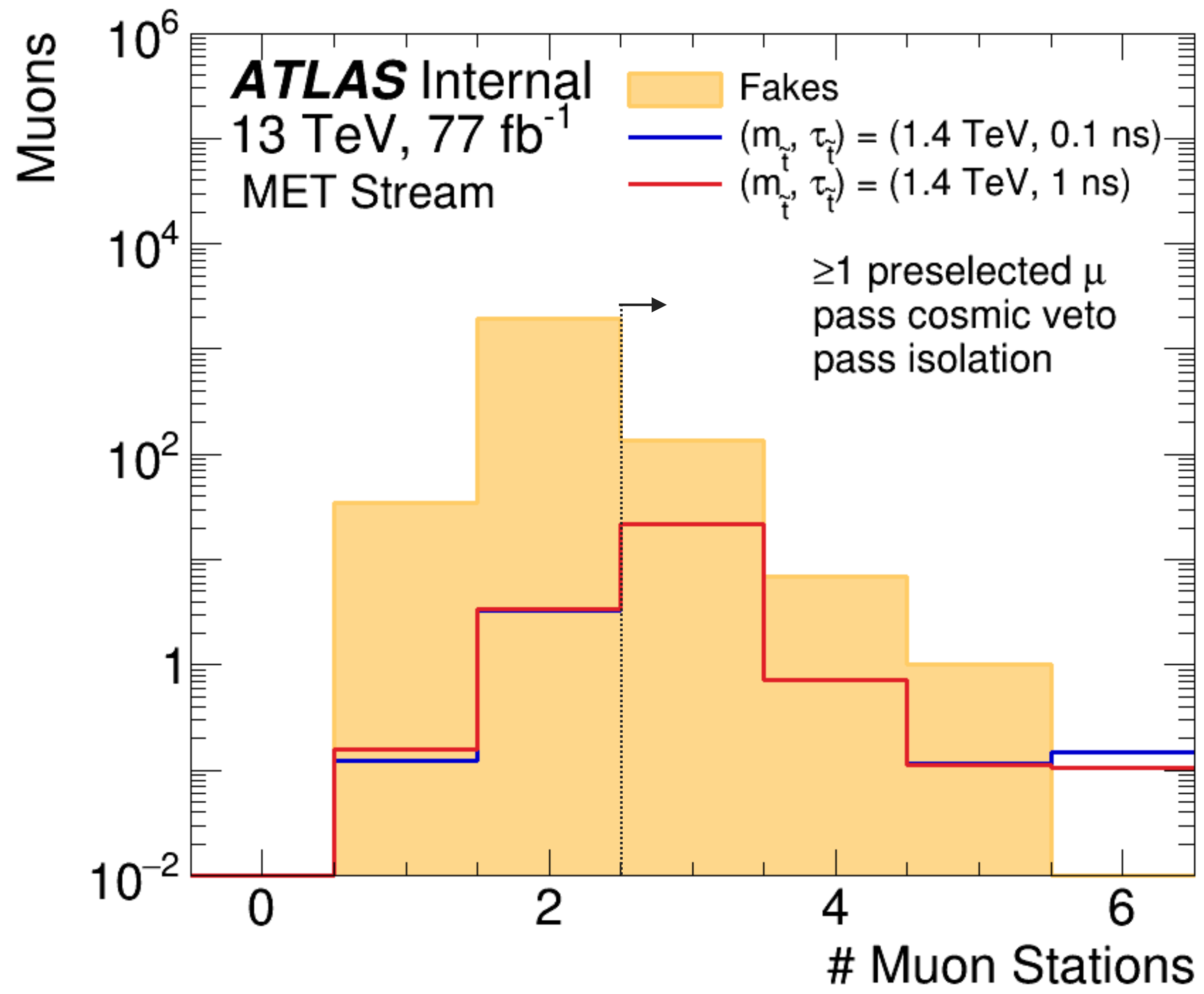


Fake Muon Veto

Can reject > 99% of fake muons by requiring

muon has a segment in all 3 muon spectrometer stations
and good quality of fit





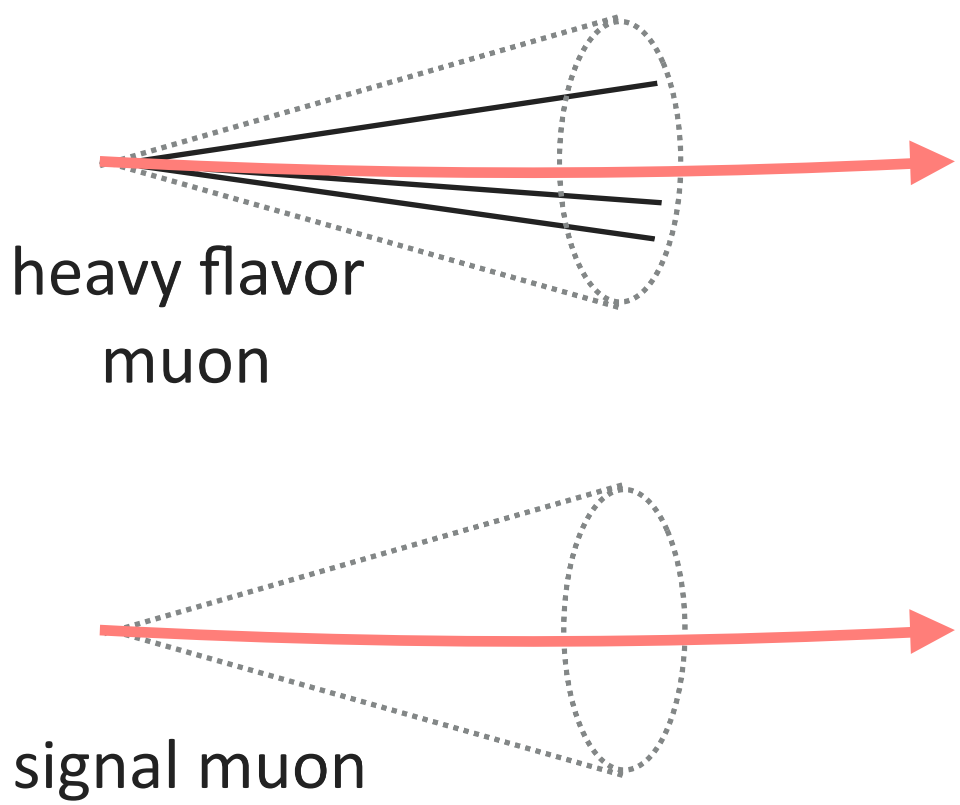
Heavy Flavor Veto

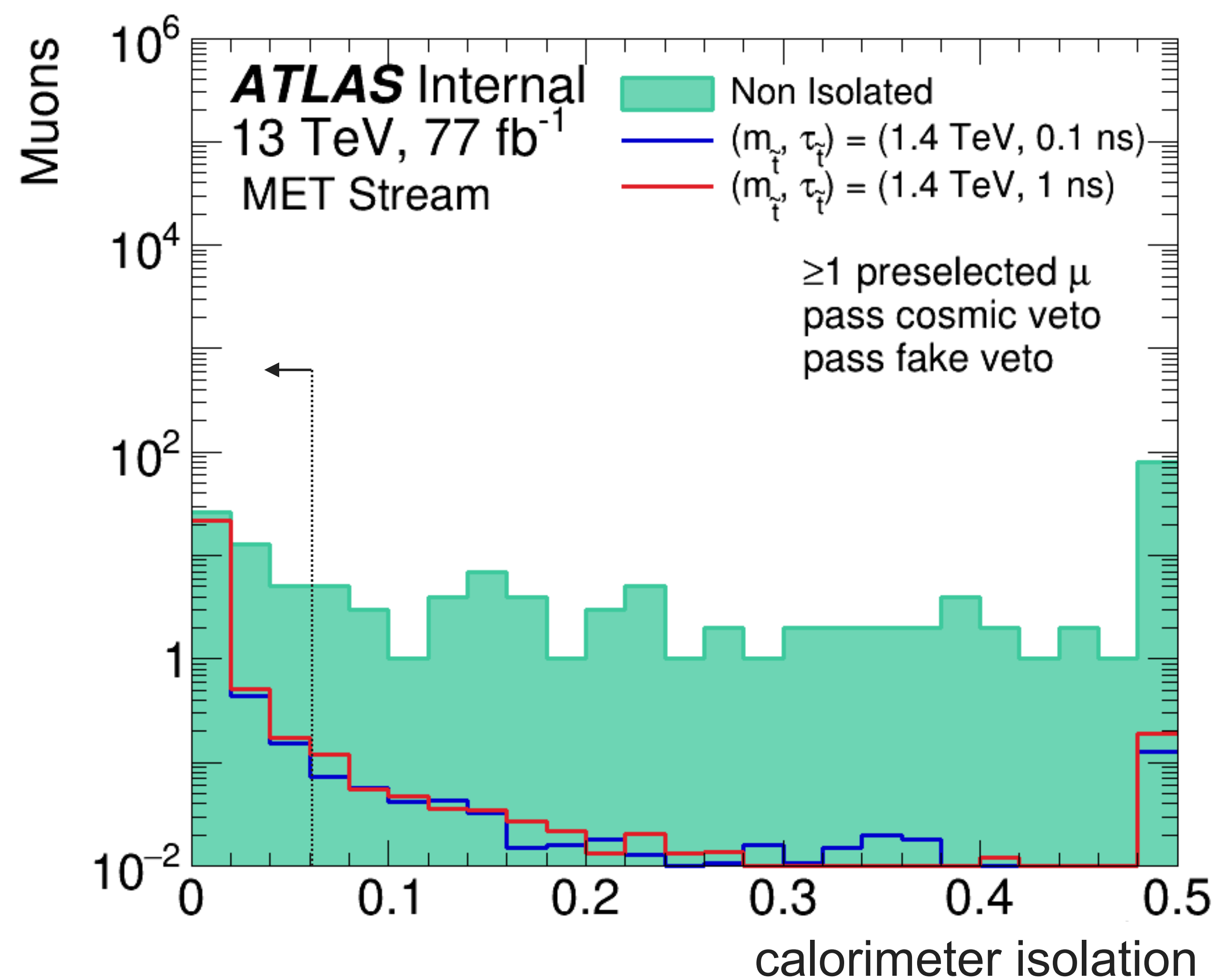
Muons from heavy flavor decays do pass |d0| > 2 mm

these muons tend to be produced inside jets

by requiring muons pass track and calorimeter isolation requirements

we can reject ~85% of heavy flavor muons and keep ~99% of signal muons





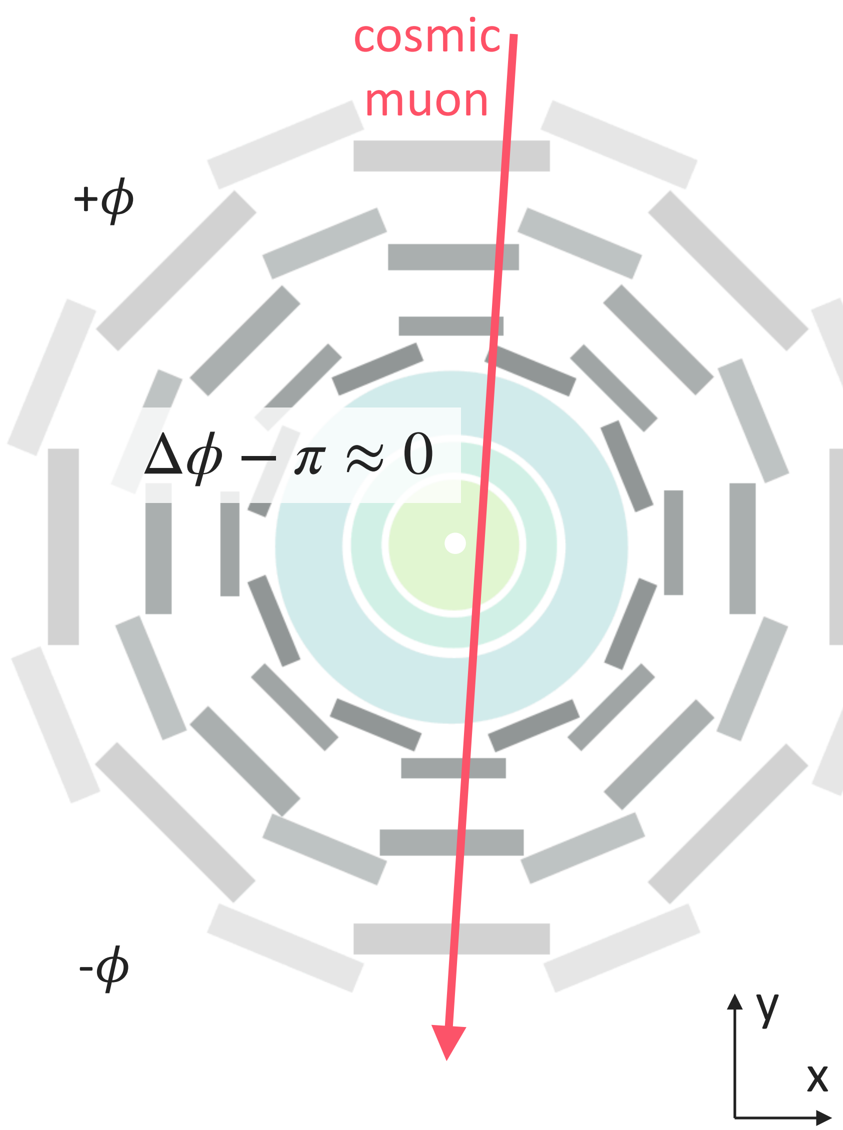
eg. track isolation

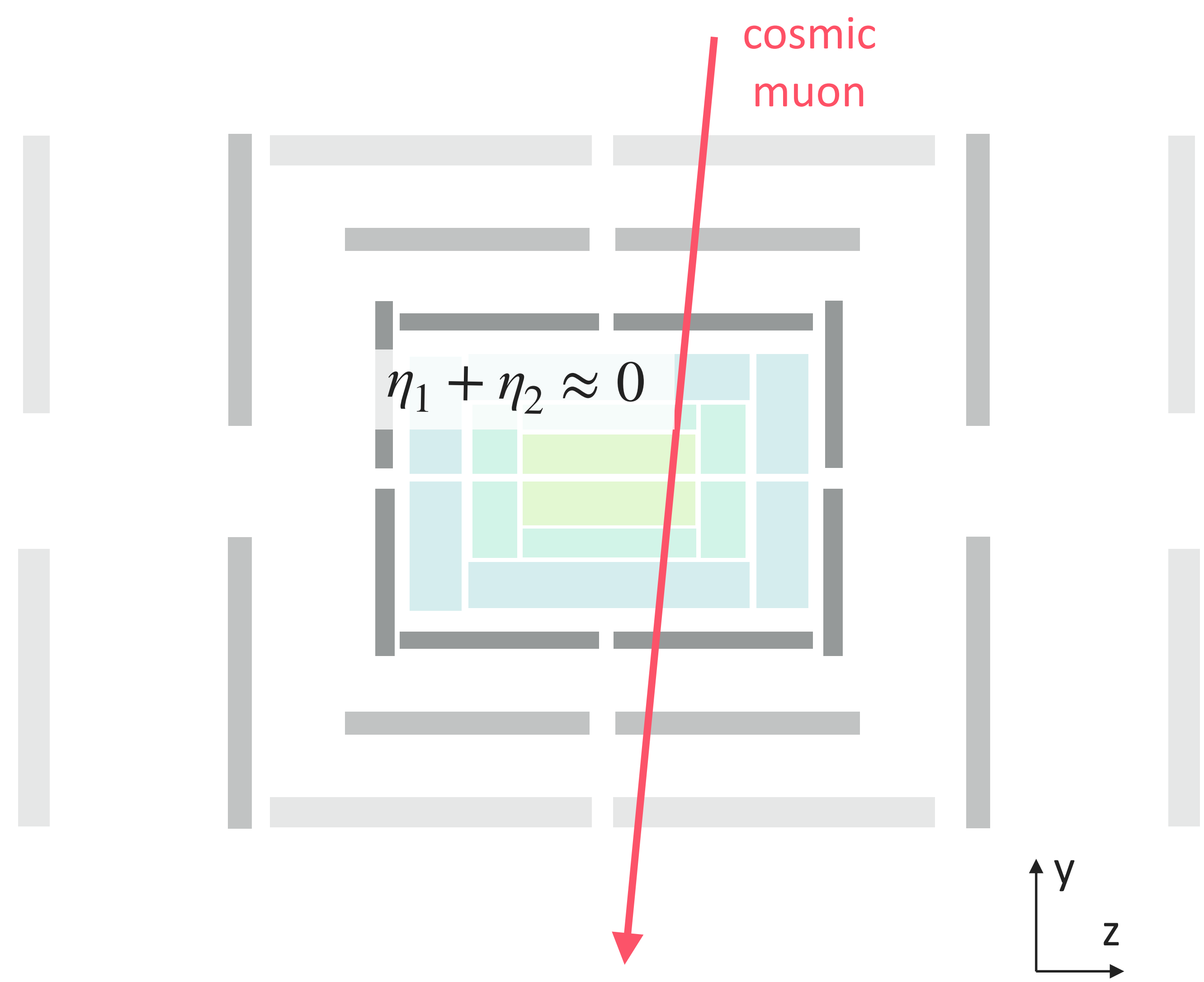
pT of tracks in cone / muon pT

Dominant background in muon triggered events - difficult to reject

Original Idea: Run 1 analysis vetoed back-to-back muons

$$\Delta R_{cosmic} = \sqrt{(\eta_1 + \eta_2)^2 + (\Delta\phi - \pi)^2} \approx 0$$





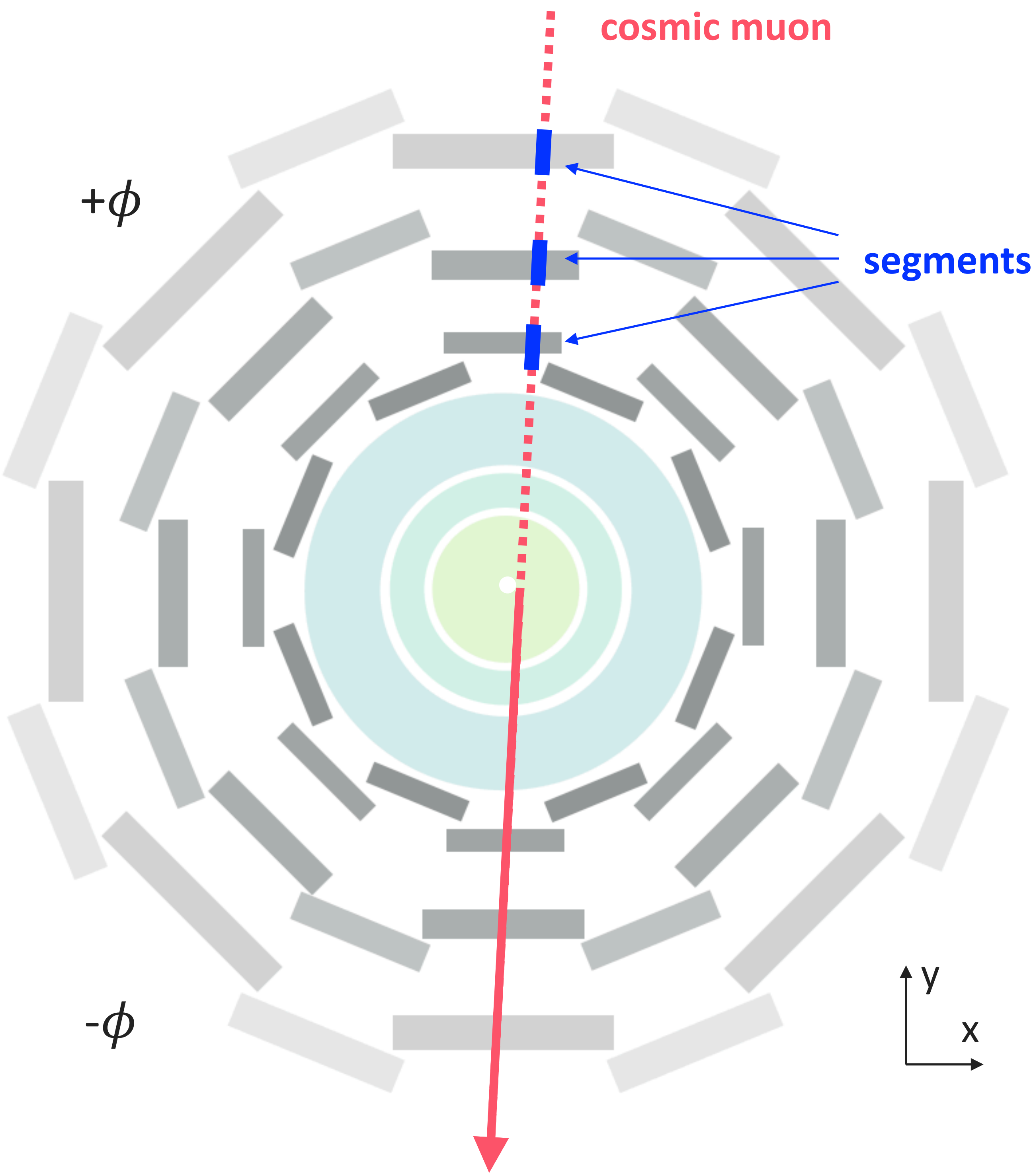
Cosmic Muons

Challenge: Run 1 veto only rejects 65% of cosmics!

often don't reconstruct $+\phi$ muon, because we're reconstructing opposite actual direction of muon, out of time with respect to collisions by ~30-70 ns

But we do reconstruct muon segments in $+\phi$!

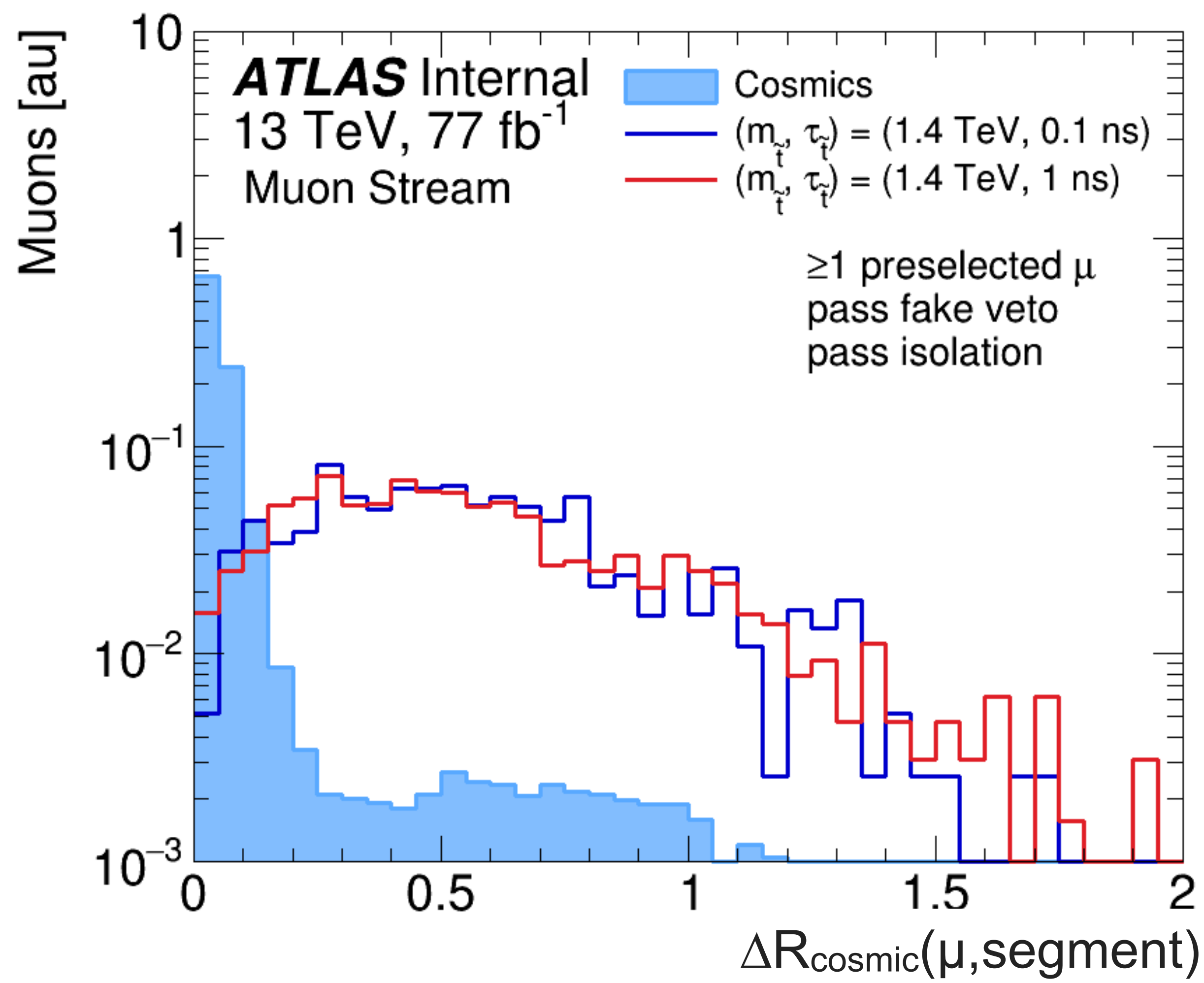
timing difference for hits within a muon chamber $\sim\mathcal{O}(1\text{ ns})$



Cosmic Veto

New idea: veto muons if back-to-back with a segment

rejects 95% of cosmics and keep 95% of signal

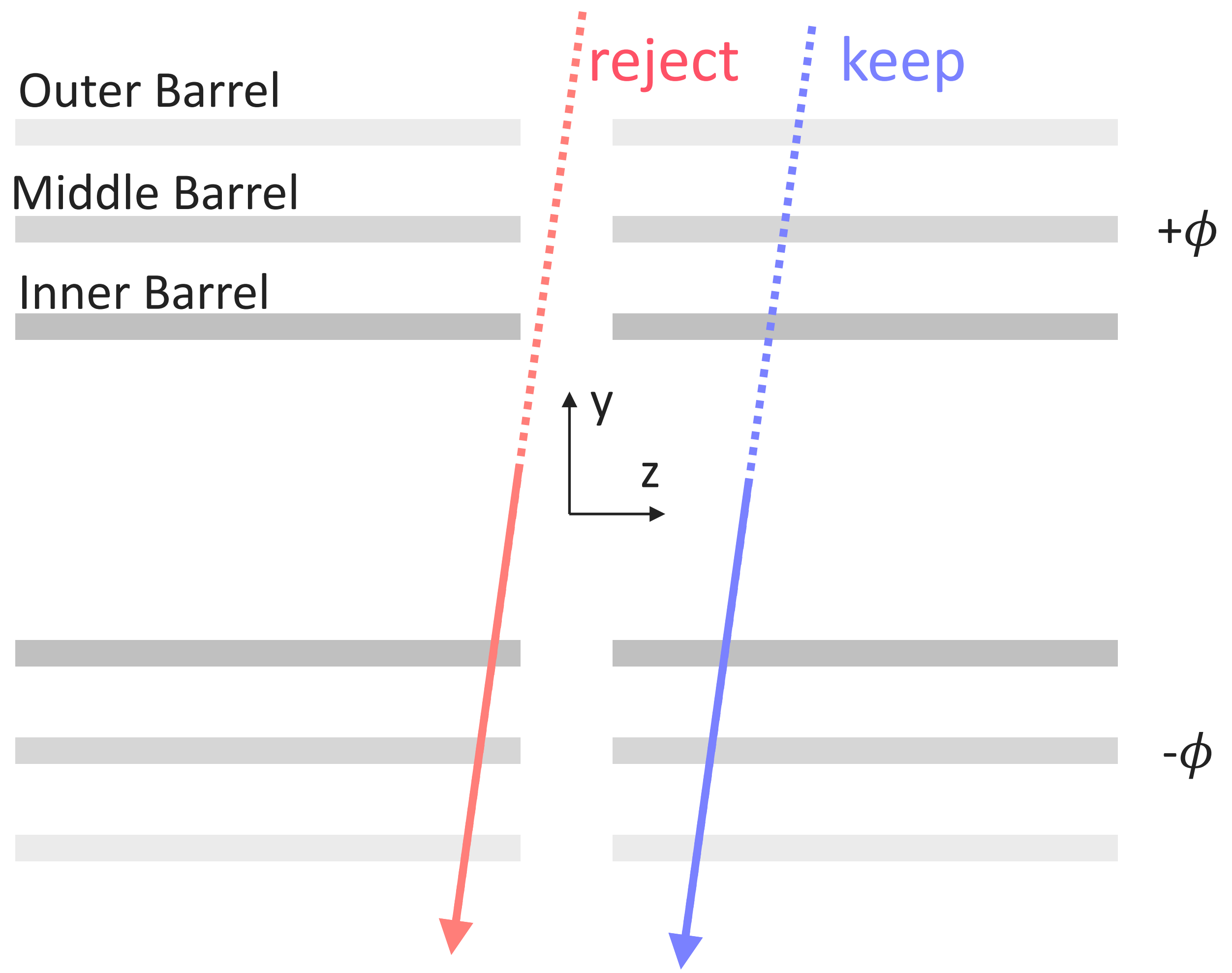


*also account for differences in segment eta-phi resolution (drift tubes point in phi) and make a geometric correction for muon displacement

But we're not done yet!

cosmics which pass the segment veto form hot spots near eta~0

→ additionally require muons to point backwards in eta-phi to regions with muon detector coverage



full cosmic veto rejects >99% of cosmics and keeps 95% of signal

allows us to loosen our displaced vertex selection with respect to run 1

Displaced Vertex Selection

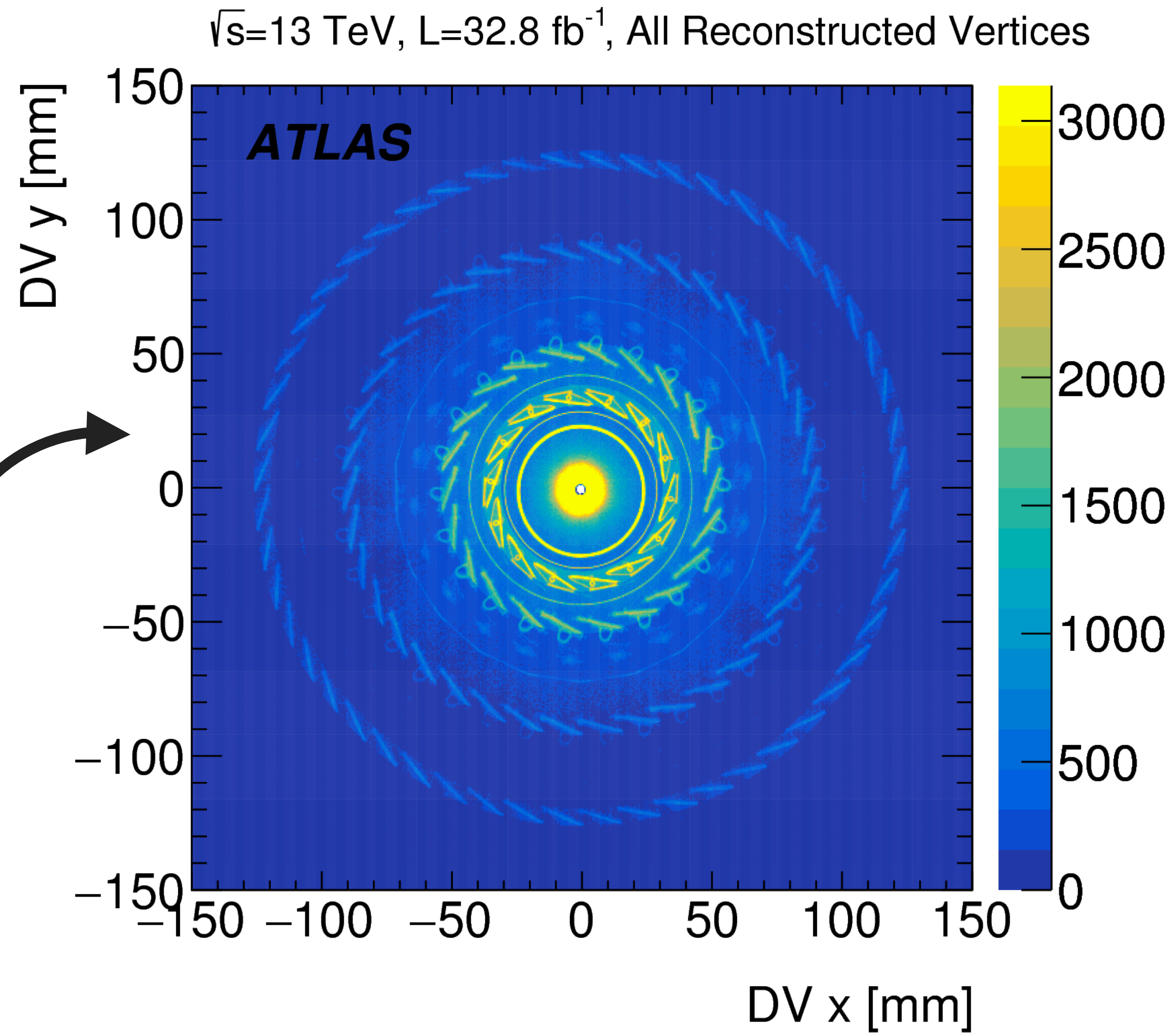
Preselection

Fiducial Volume
Rxy < 300 mm |z| < 300 mm

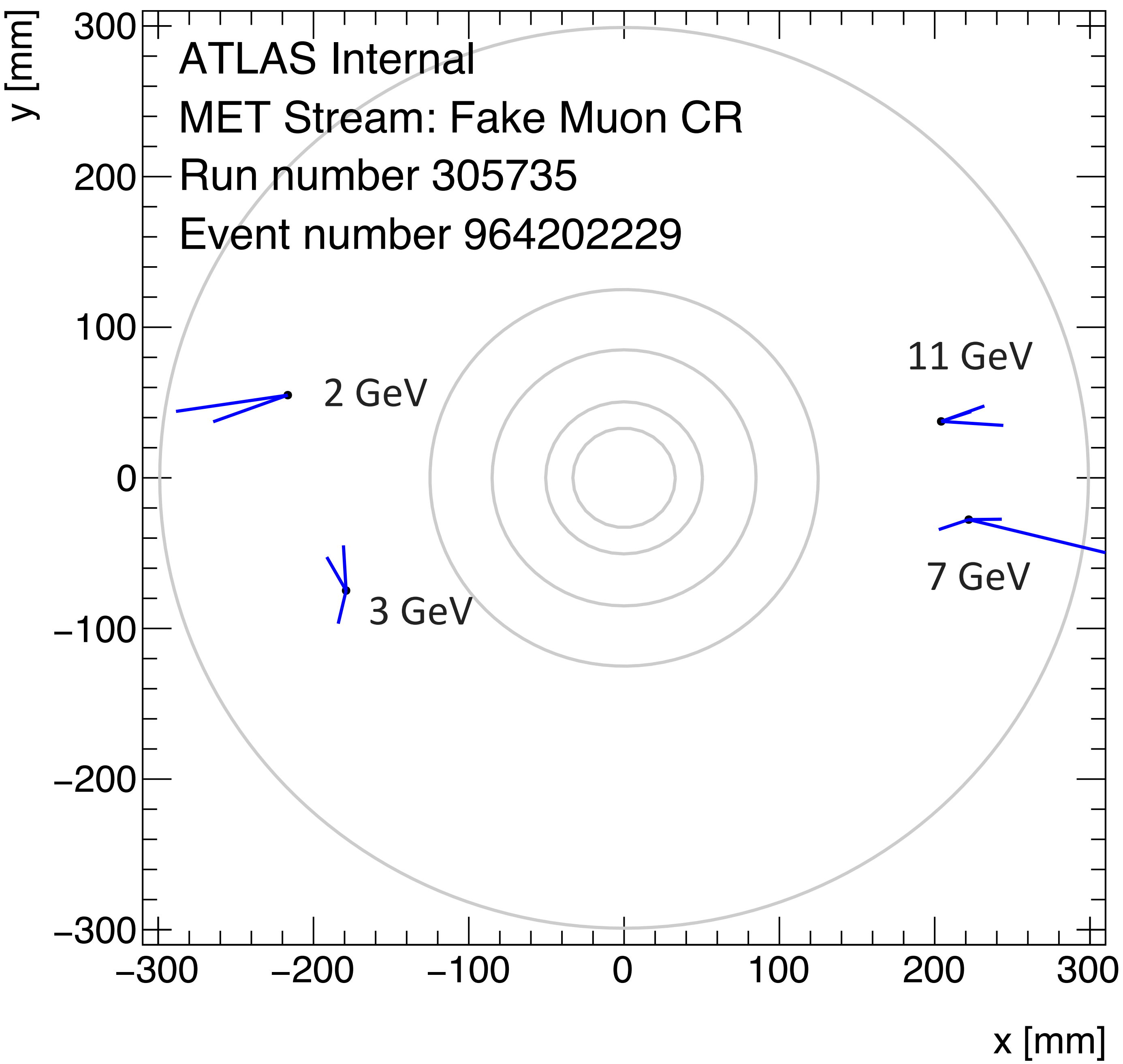
Distance from displaced vertex to any primary vertex, in transverse plane > 4 mm

Quality: $\chi^2/N_{DoF} < 5$

Material Veto:
reject vertices with (r,z,ϕ) in regions of material



Final Displaced Vertex Selection



After preselection most DVs from random track crossings

tracks with low pT form low mass and low track multiplicity vertices

Final Selection

displaced vertices must have

1. at least 3 tracks

&

2. mass > 15 GeV

~10%-20% improvement in signal efficiency with respect to Run 1 selection

Overview of results

Selection	MET Stream	Muon Stream
Cosmic Muons	<0.008	**1.02** ± 0.06 ± 0.07
Heavy Flavor	**0.14** ± 0.14 ± 0.04	**0.28** ± 0.20 ± 0.07
Fake Muons	**0.12** ± 0.02 ± 0.12	**0.01** ± 0.01 ± 0.01
Total Expected Background	**0.26** ± 0.14 ± 0.13	**1.31** ± 0.21 ± 0.10
Expected Signal (1.4 TeV, 0.1 ns)	**12.3** ± 0.06	**0.45** ± 0.13
Expected Signal (1.4 TeV, 1 ns)	**4.7** ± 0.41	**0.21** ± 0.08

**work in progress, especially systematic uncertainties & MC statistics*

Reminder: MET stream drives sensitivity to our benchmark model but we keep the Muon Stream to retain sensitivity to other signals

A word on systematic uncertainties

Signal

15-30% Cross Section
~10% Tracking + Vertexing Efficiency
~10% Pileup Reweighting
~2% Muon Trigger
~2% Muon Identification
~2% Luminosity

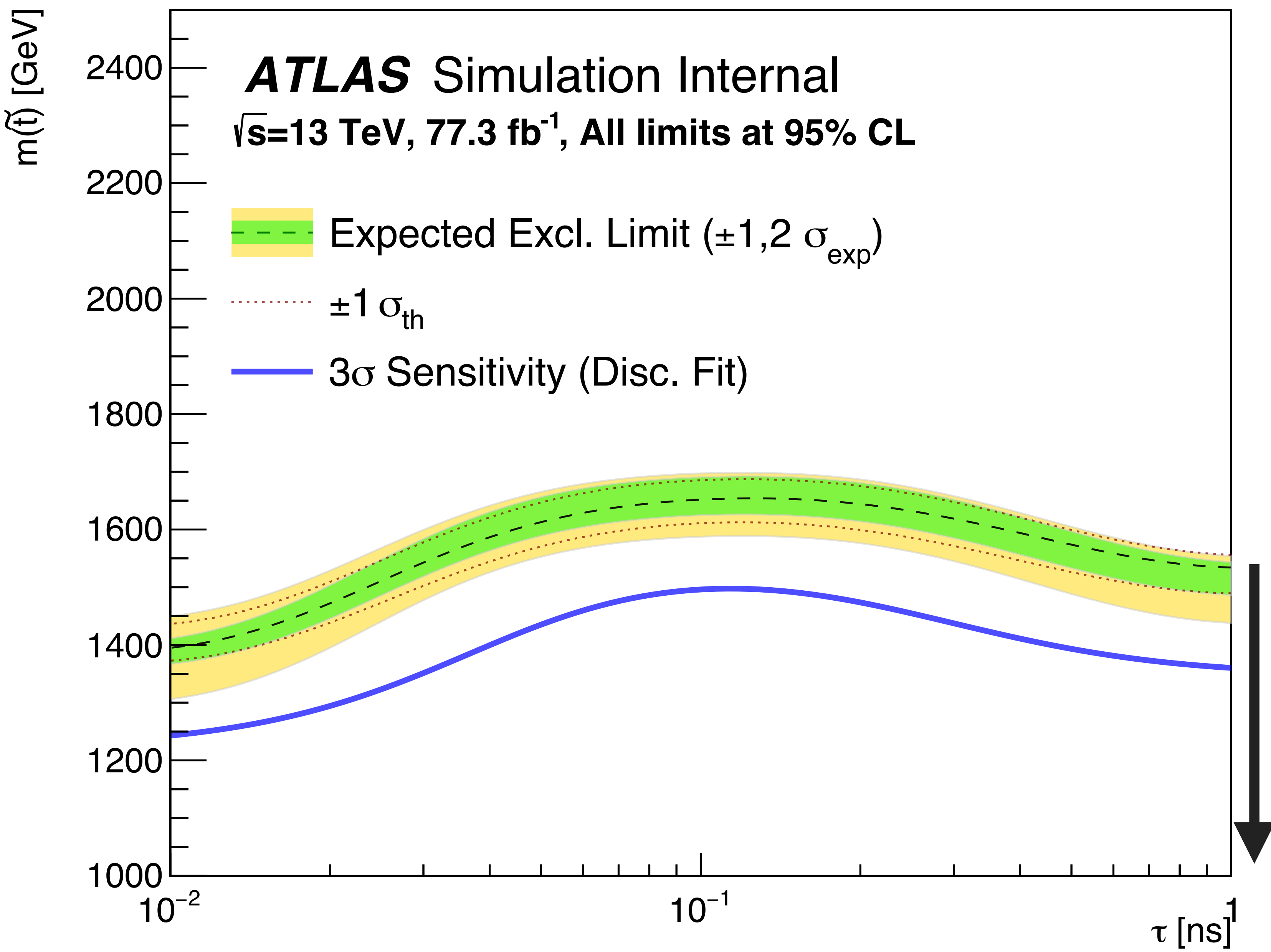
Backgrounds

~50% uncertainty on total background in MET Stream
Heavy Flavor: statistics in control regions
Fakes: statistics, and possible correlation between vertex properties & fake muons

Sensitivity/Predictions

Expected sensitivity for different stop masses and lifetimes

with 2016-2017 data



For reference:

Converting # selected signal events to sensitivity lines

3 events → exclusion

5 events → 3σ

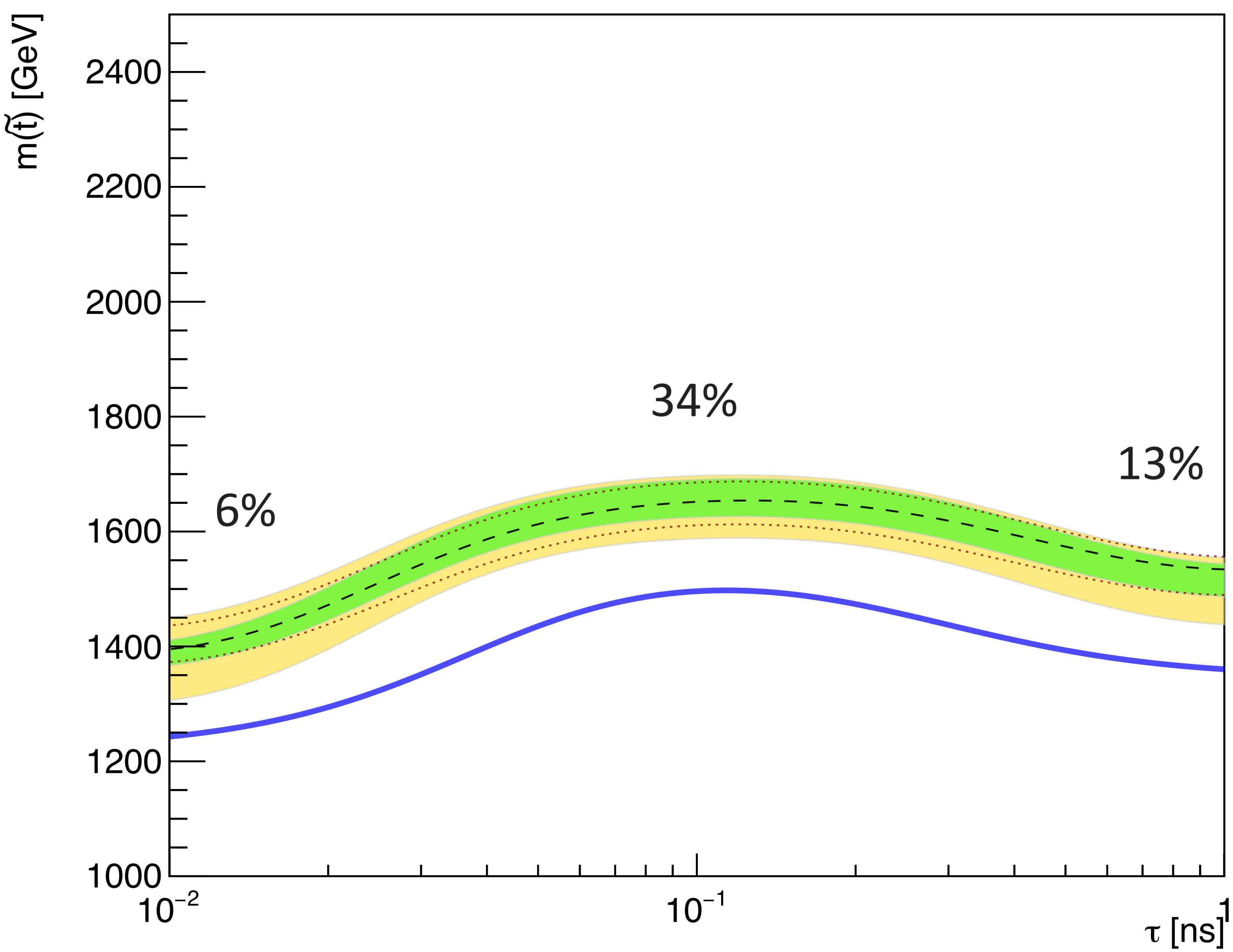
Increasing XS

can exclude/discover masses and lifetimes below curve

Sensitivity/Predictions

Sensitivity Shaped by Signal Acceptance x Efficiency

acceptance primarily related to signal lifetime



small lifetimes

|d0| > 2 mm

DV-PV distance

large lifetimes

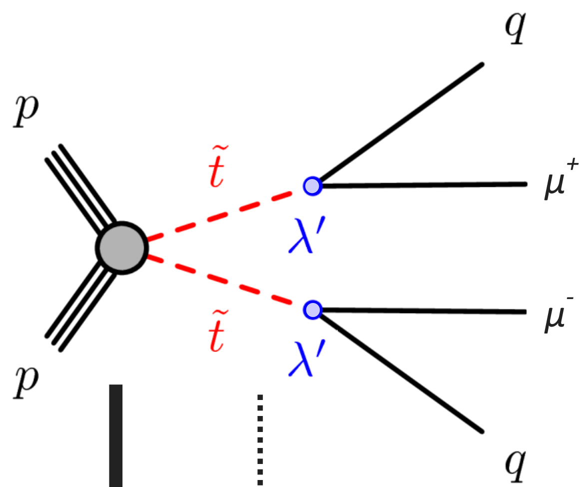
Fiducial volume

Rxy < 300 mm

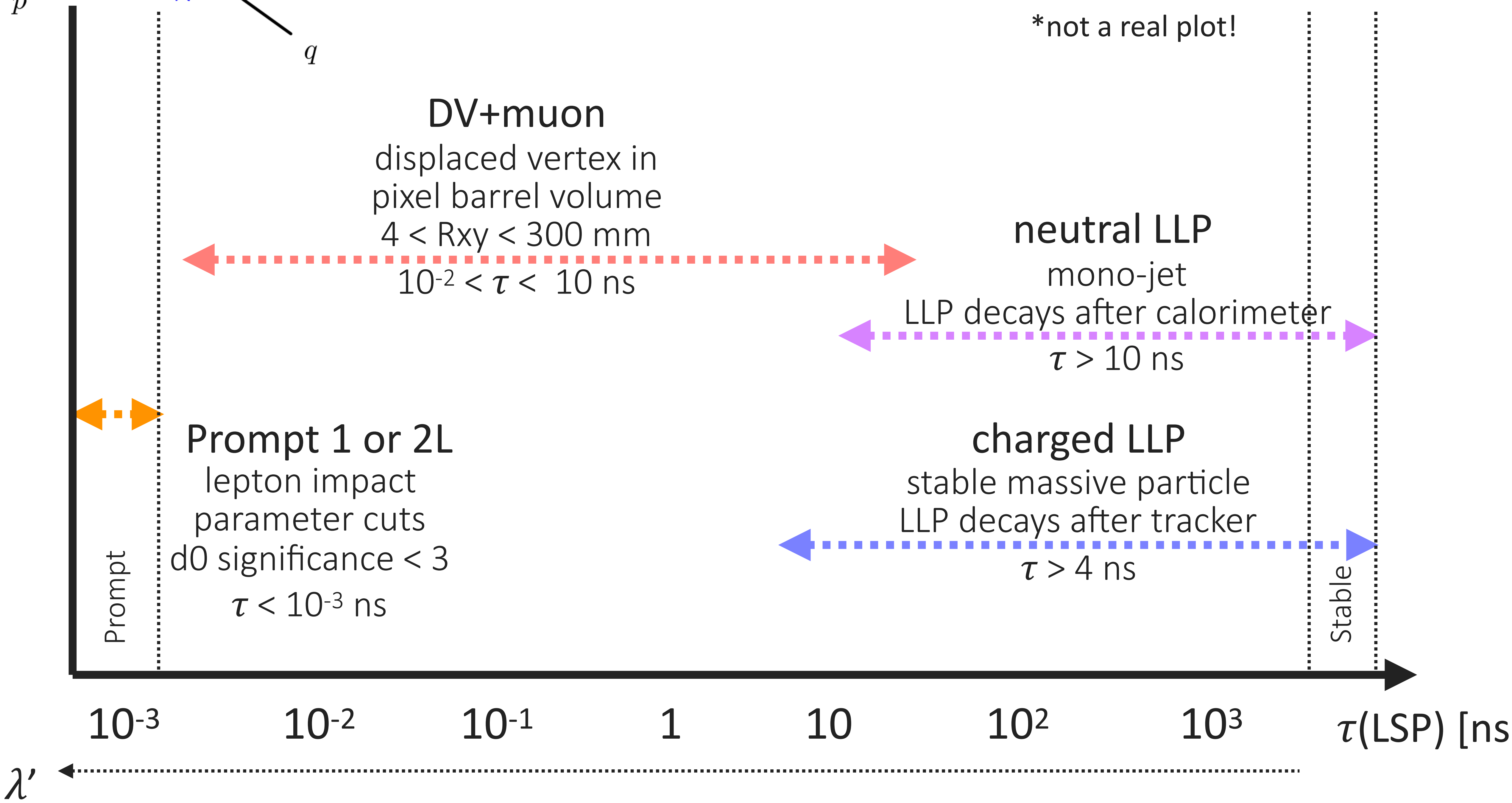
and reduced

vertexing efficiency

How we expect to compare to other analyses



DV+muon uniquely sensitive to decays inside ATLAS Inner detector



Future Prospects

Improvements to current analysis

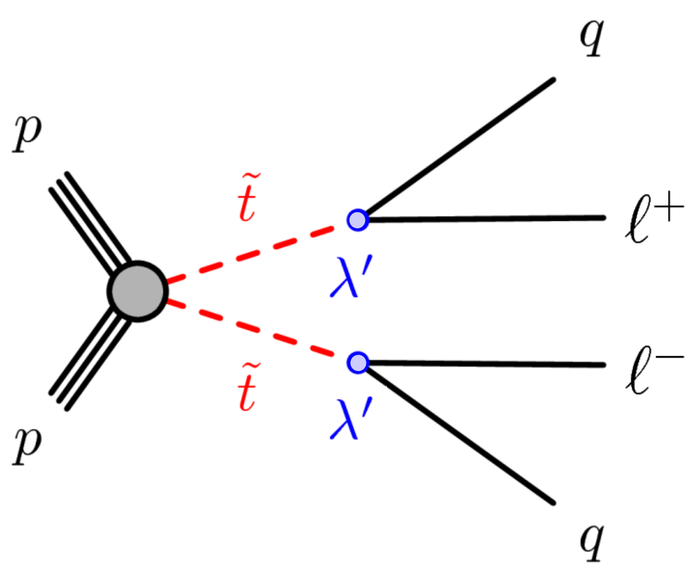
try to loosen |d0| and distance(DV-PV) requirements

reduce large radius tracking fake rate at higher pileup and improve vertexing efficiency at large radii

Run 3: planned improvements to muon trigger

	Run 1 2010-2012	Run 2 2015-2018	Run 3 2021-2023	HL-LHC 2026-
$\sqrt{s}$	7-8 TeV	13 TeV	14 TeV	14 TeV
Integrated Luminosity	26 fb^{-1}	140 fb^{-1}	150 fb^{-1}	3000 fb^{-1}

Future Prospects



Other interesting long-lived particle searches

direct detection of charged LLPs using pixel dE/dx

targets slightly longer lifetimes, $\tau > 4$ ns

interesting in Run 3 because of new trigger opportunities

	Run 1 2010-2012	Run 2 2015-2018	★ Run 3 2021-2023	HL-LHC 2026-
$\sqrt{s}$	7-8 TeV	13 TeV	14 TeV	14 TeV
Integrated Luminosity	26 fb^{-1}	140 fb^{-1}	150 fb^{-1}	3000 fb^{-1}

ATLAS Muon Spectrometer

Challenges at high instantaneous luminosity

LHC Schedule

Looking forward to physics at High Luminosity LHC

	Run 1 2010-2012	Run 2 2015-2018	Run 3 2021-2023	HL-LHC 2026-
$\sqrt{s}$	7-8 TeV	13 TeV	14 TeV	14 TeV
Integrated Luminosity	26 fb^{-1}	140 fb^{-1}	150 fb^{-1}	3000 fb^{-1}

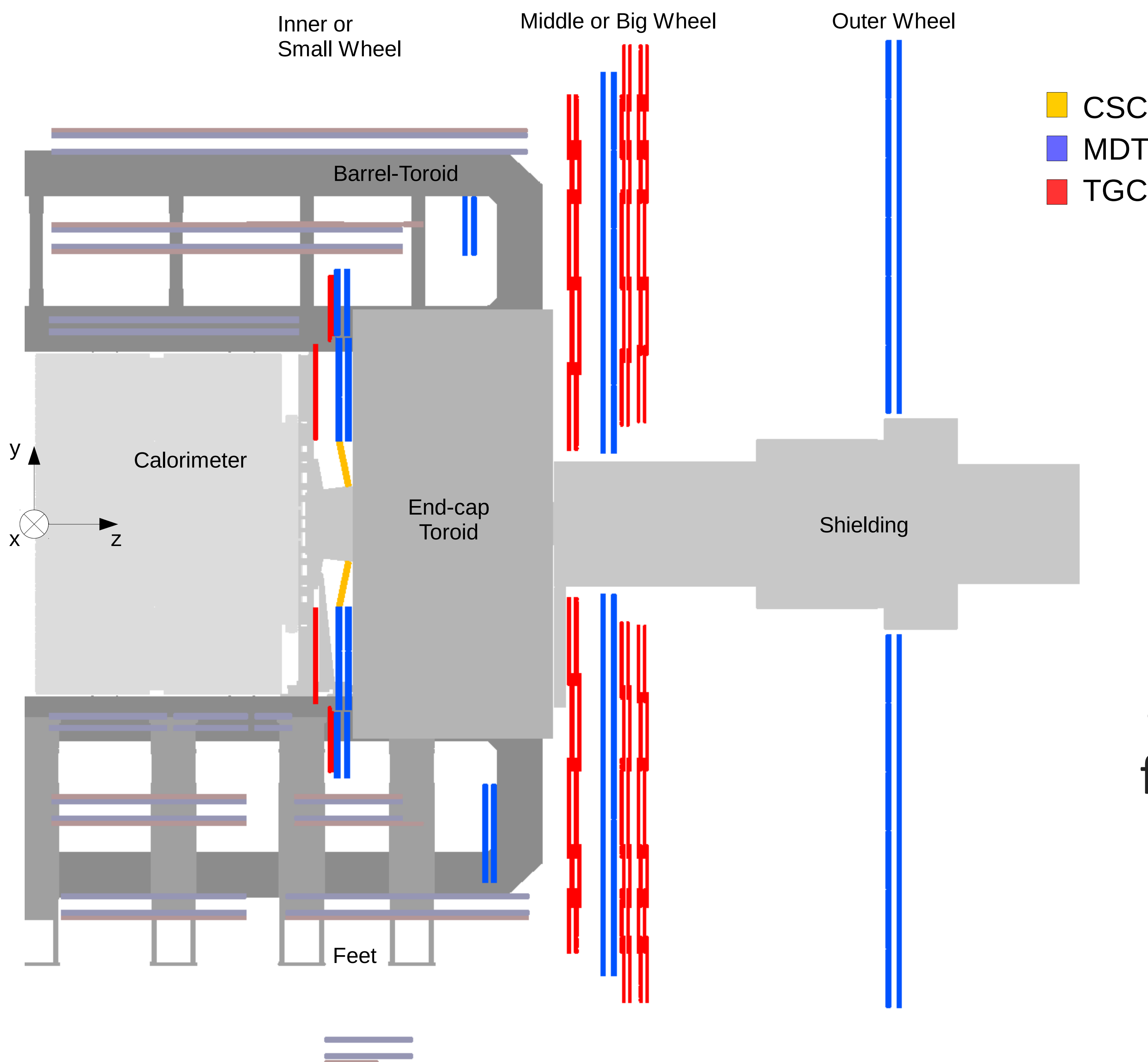
LHC Schedule

Looking forward to physics at High Luminosity LHC

	Run 1 2010-2012	Run 2 2015-2018	Run 3 2021-2023	HL-LHC 2026-
$\sqrt{s}$	7-8 TeV	13 TeV	14 TeV	14 TeV
Integrated Luminosity	26 fb^{-1}	140 fb^{-1}	150 fb^{-1}	3000 fb^{-1}
Max. Inst. Luminosity	$8 \cdot 10^{33}$ $cm^{-2}s^{-1}$	$2 \cdot 10^{34}$ $cm^{-2}s^{-1}$	$2 \cdot 10^{34}$ $cm^{-2}s^{-1}$	$7 \cdot 10^{34}$ $cm^{-2}s^{-1}$

LHC instantaneous luminosity will be x7 higher than design values
need to make sure ATLAS maintains excellent performance

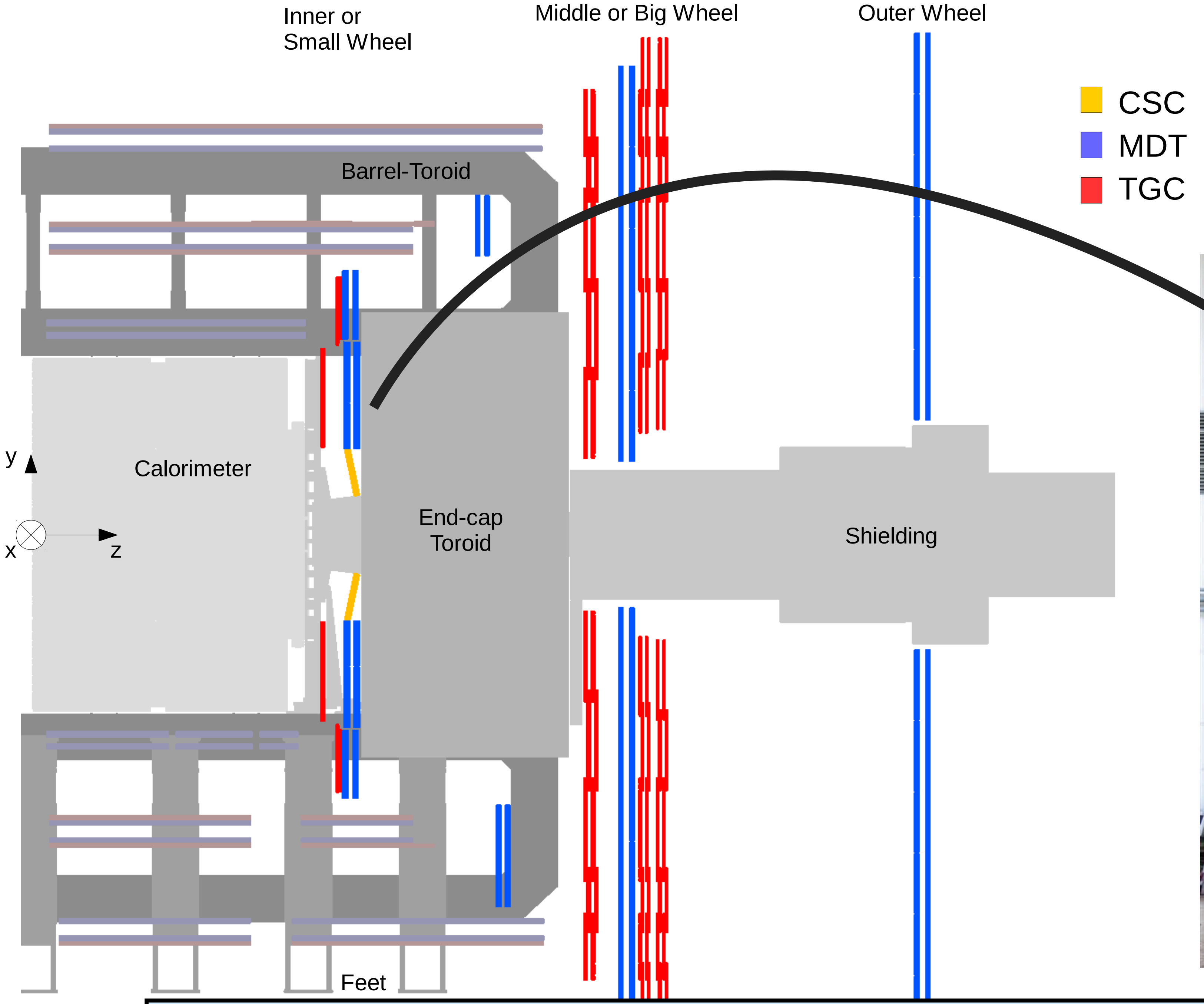
Reminder: Muon Endcap Geometry

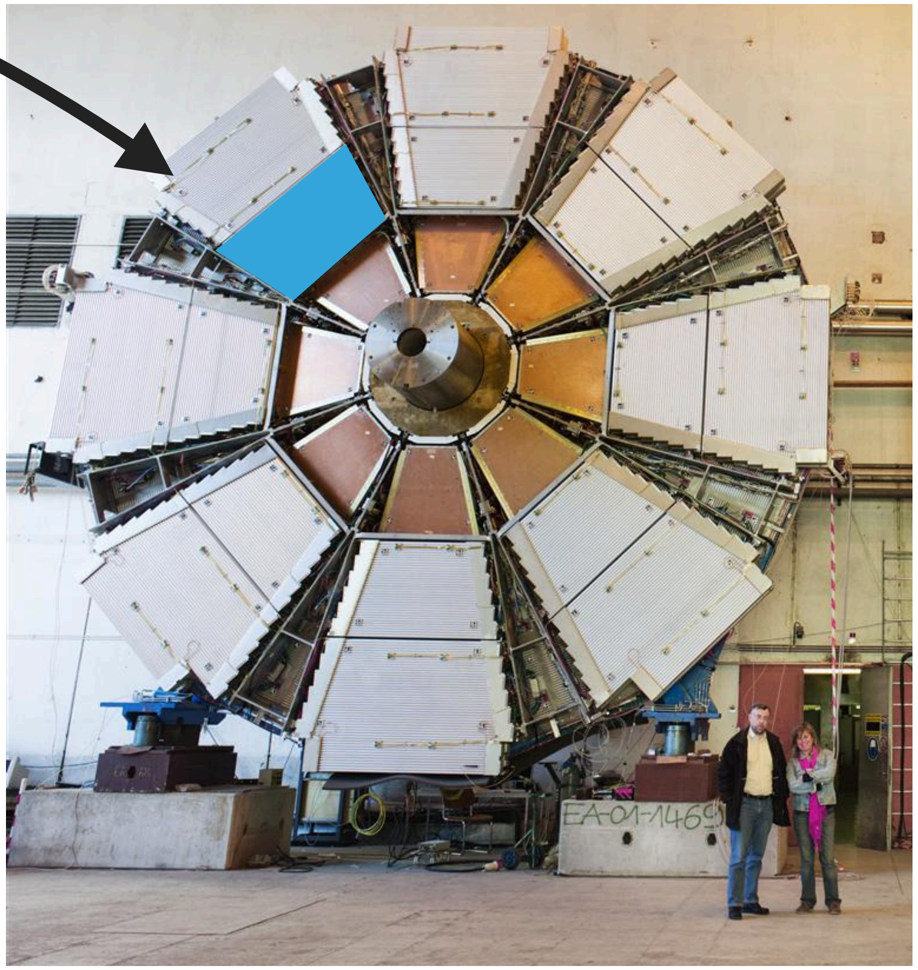


Cathode Strip Chambers and Monitored Drift Tubes for precision muon tracking

Thin Gap Chambers for muon triggering

Reminder: Muon Endcap Geometry





Focus on Small Wheel, and ask the question

Can the Monitored Drift Tubes survive at High Luminosity LHC?

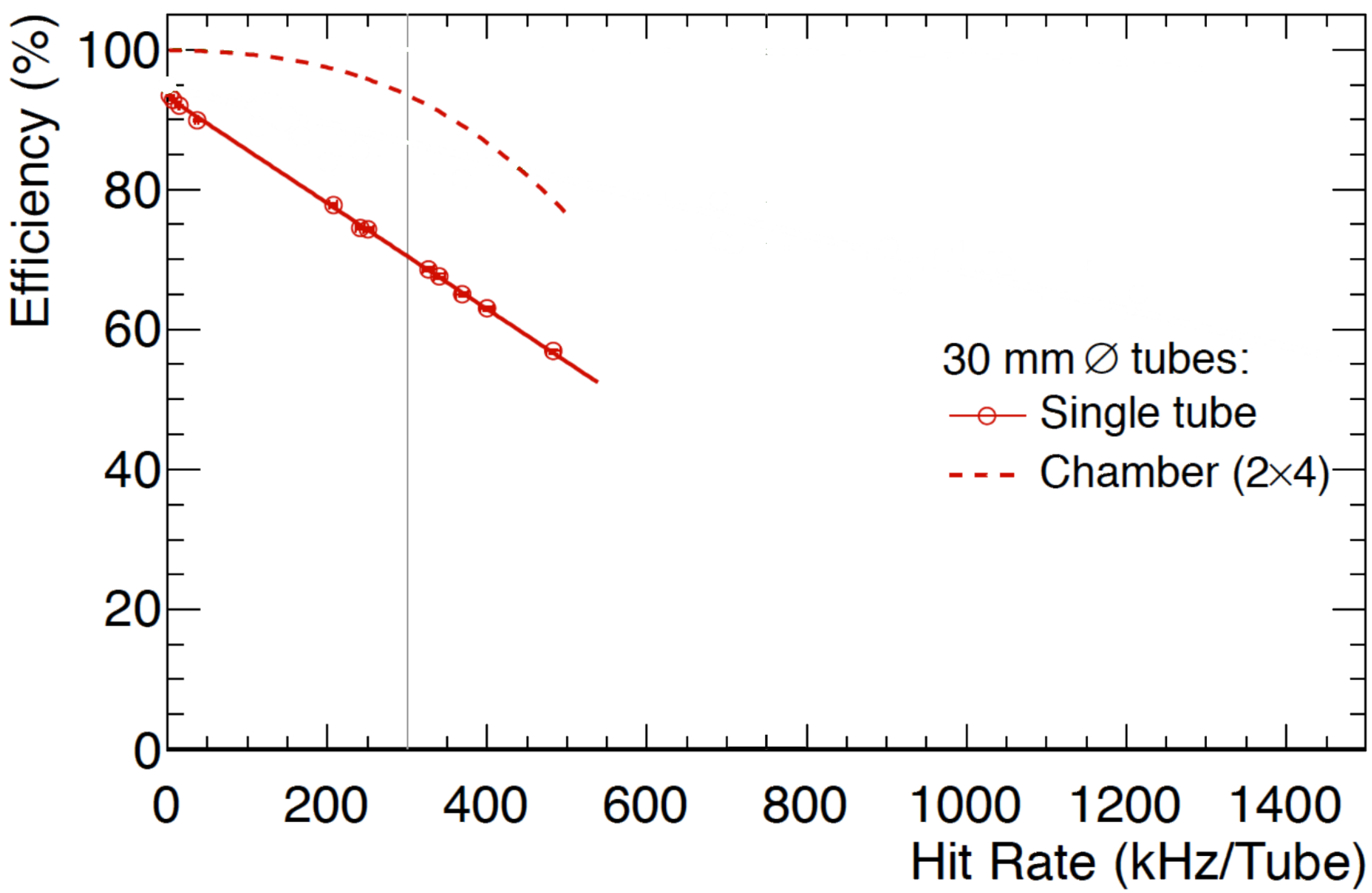
What is the maximum hit rate we can sustain?

MDTs have a maximum drift time of 750 ns → dead time

hit efficiency v. hit rate, measured using test beam data

hit rates of 500 Hz/cm^2 or 300 kHz/tube result in 35% single tube efficiency loss
any higher results in drastic losses to muon resolution and efficiency

ATLAS-TDR-020



When/where do we reach maximum rate?

In ATLAS hit rate depends on

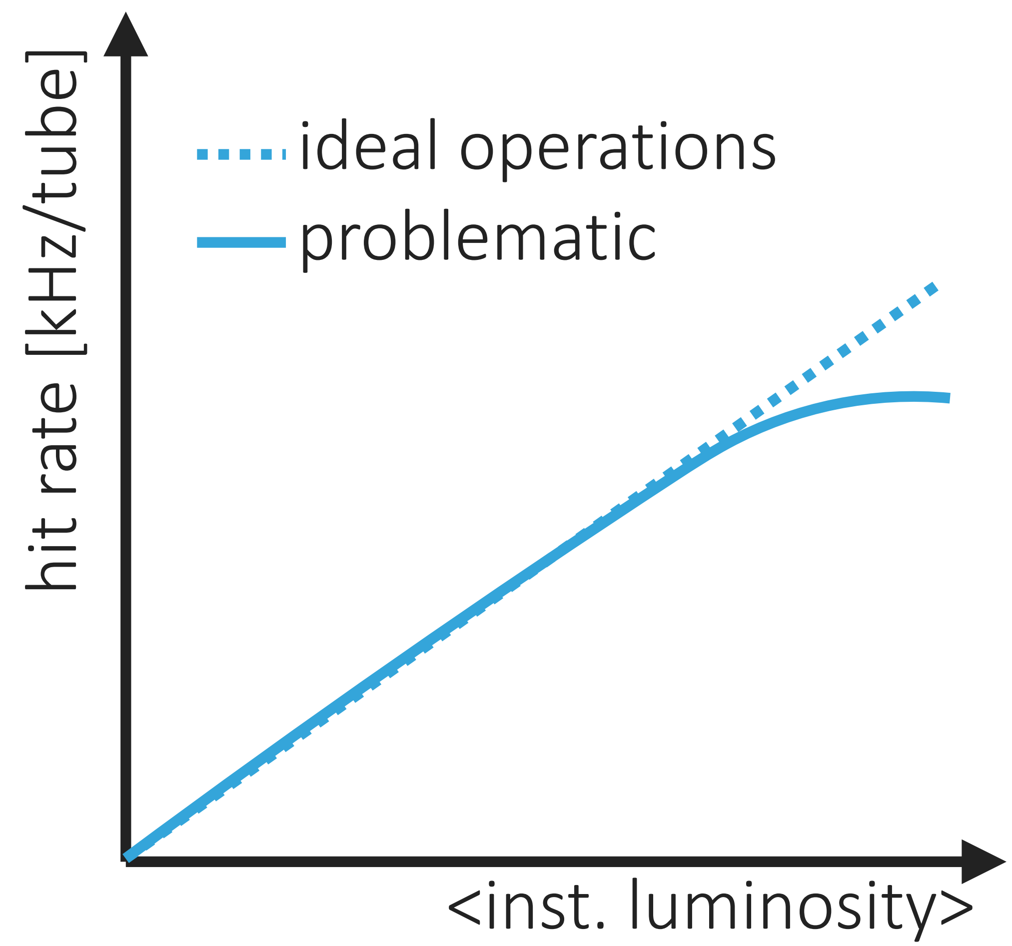
luminosity, # bunches
position in Rxy, Z
geometry, shielding

Most interested in hit rates v. luminosity

Why we make this plot

1. linear relationship is indicative of good operations
2. extrapolate to higher luminosity, will our detectors work at HL-LHC?

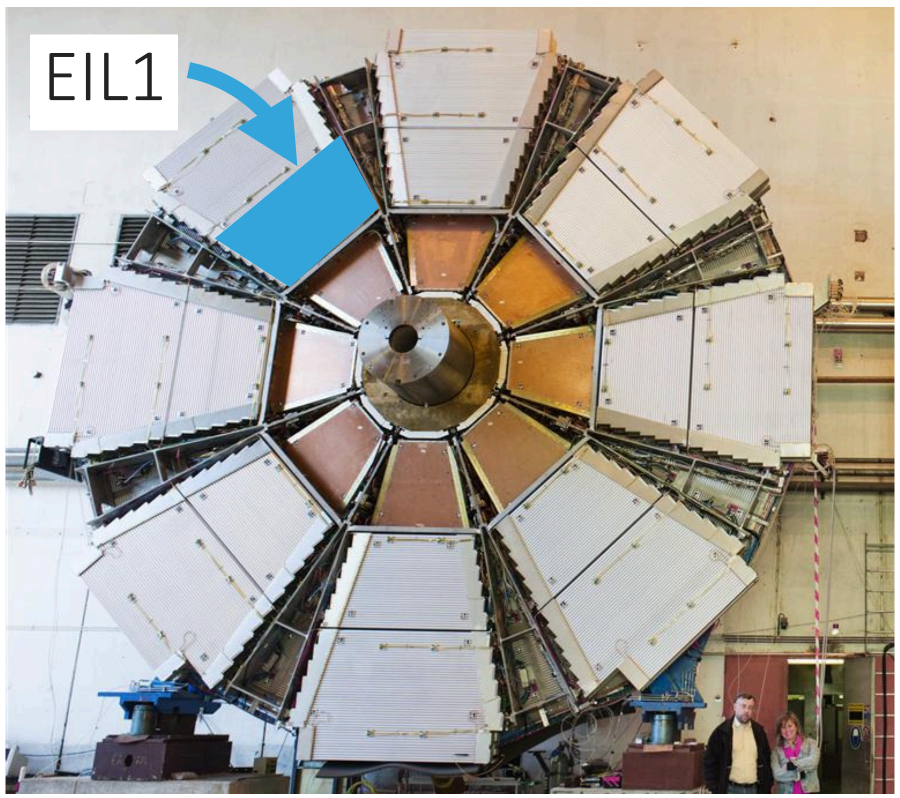
hit rate = #hits/event / livetime

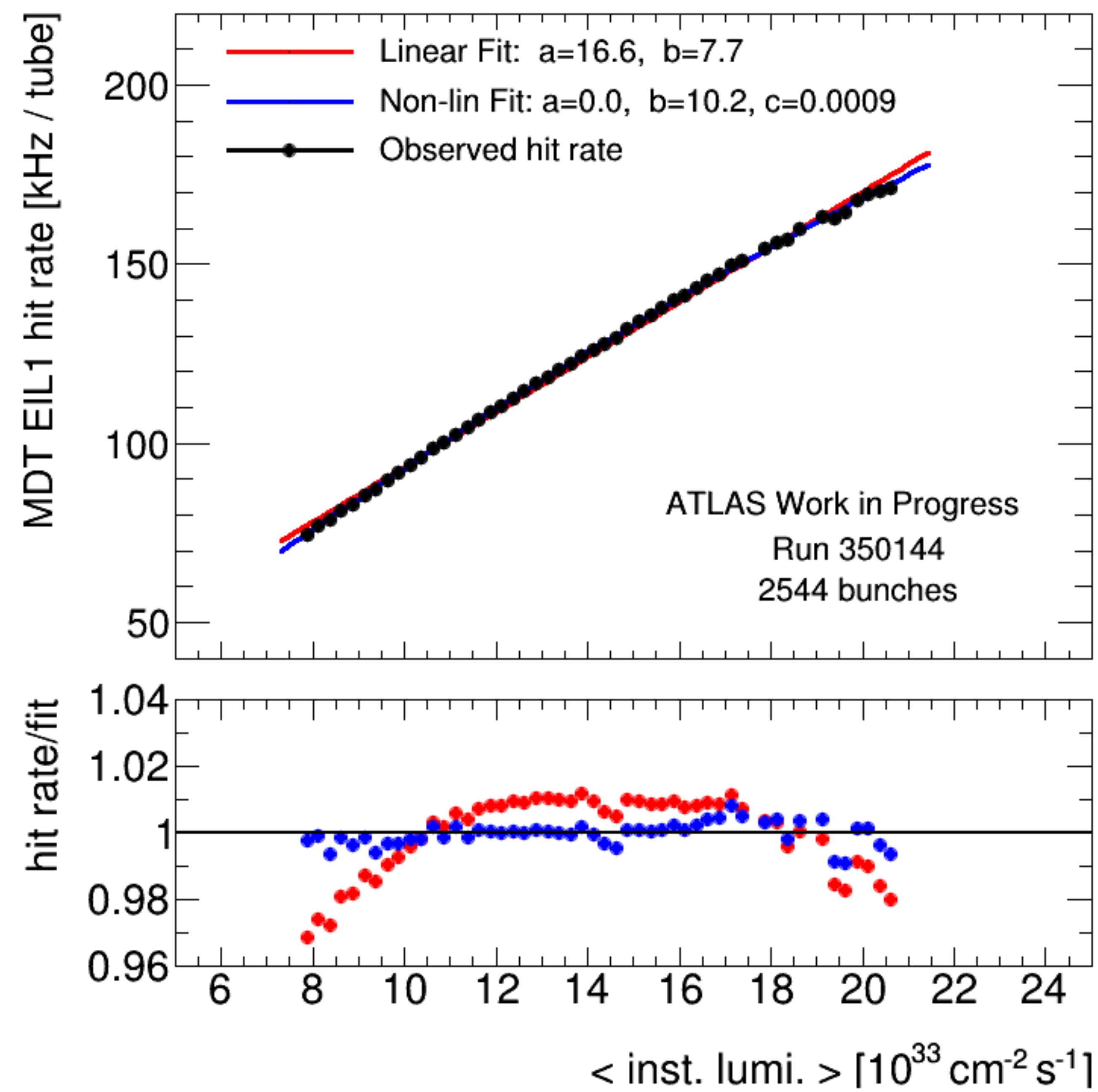


*not a real plot!

MDT Hit rates in Run 2

2018: non-linear hit rates observed in Inner Endcap!

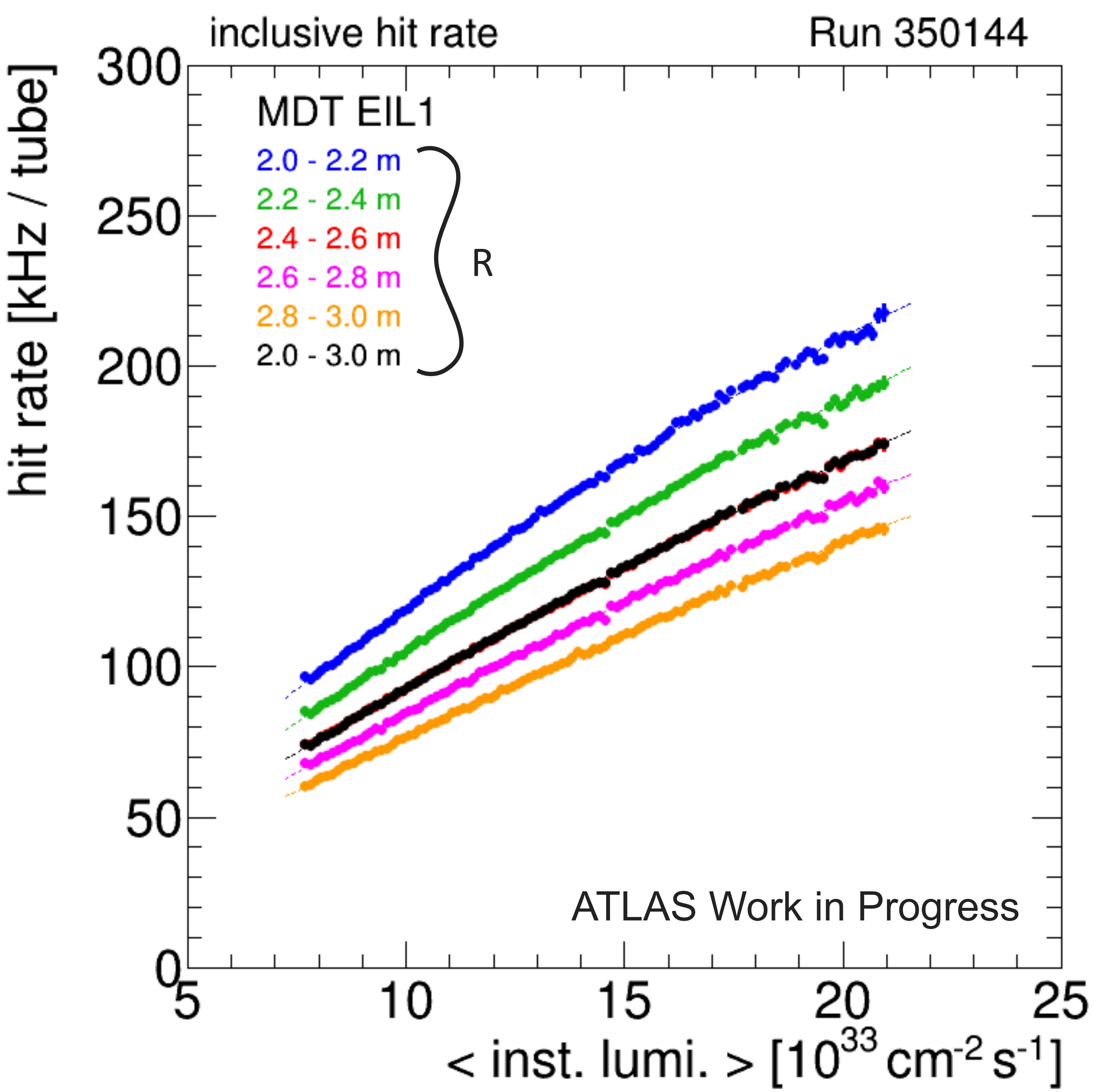




non-linearity consistent with effects from dead time → new model

observed hit rate ~ $A + B \cdot \mathscr{L} - C \cdot B^2 \cdot \mathscr{L}$

1. Characterizing performance in Run 2



From data we can measure “C”
8.6% efficiency loss
for each 100 kHz/tube
increase in delivered hit rate

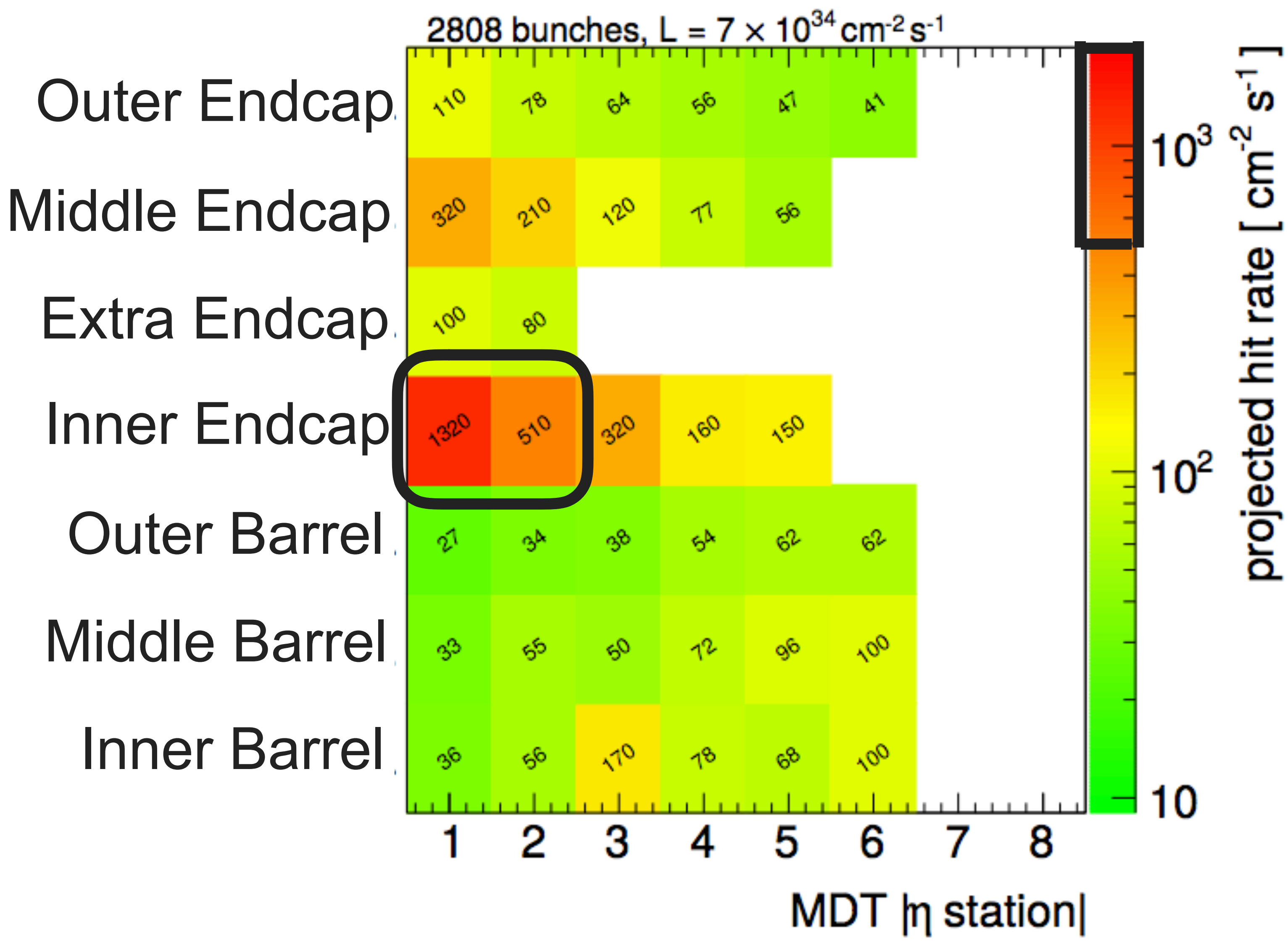
In the hottest tubes of MDT corresponds to ~20% loss in single hit efficiency at $2.0 \cdot 10^{34}$ cm^{-2}s^{-1}

This result was expected!
and is ok for Run 3*

*barring changes in shielding

2. Making Projections to HL-LHC

MDT Large Sector Hit Rate Projections at HL-LHC
using extrapolation from 2015 data
Phase II Muon TDR - ATLAS-TDR-026



Hit rates exceed maximum allowed 500 Hz/cm^2

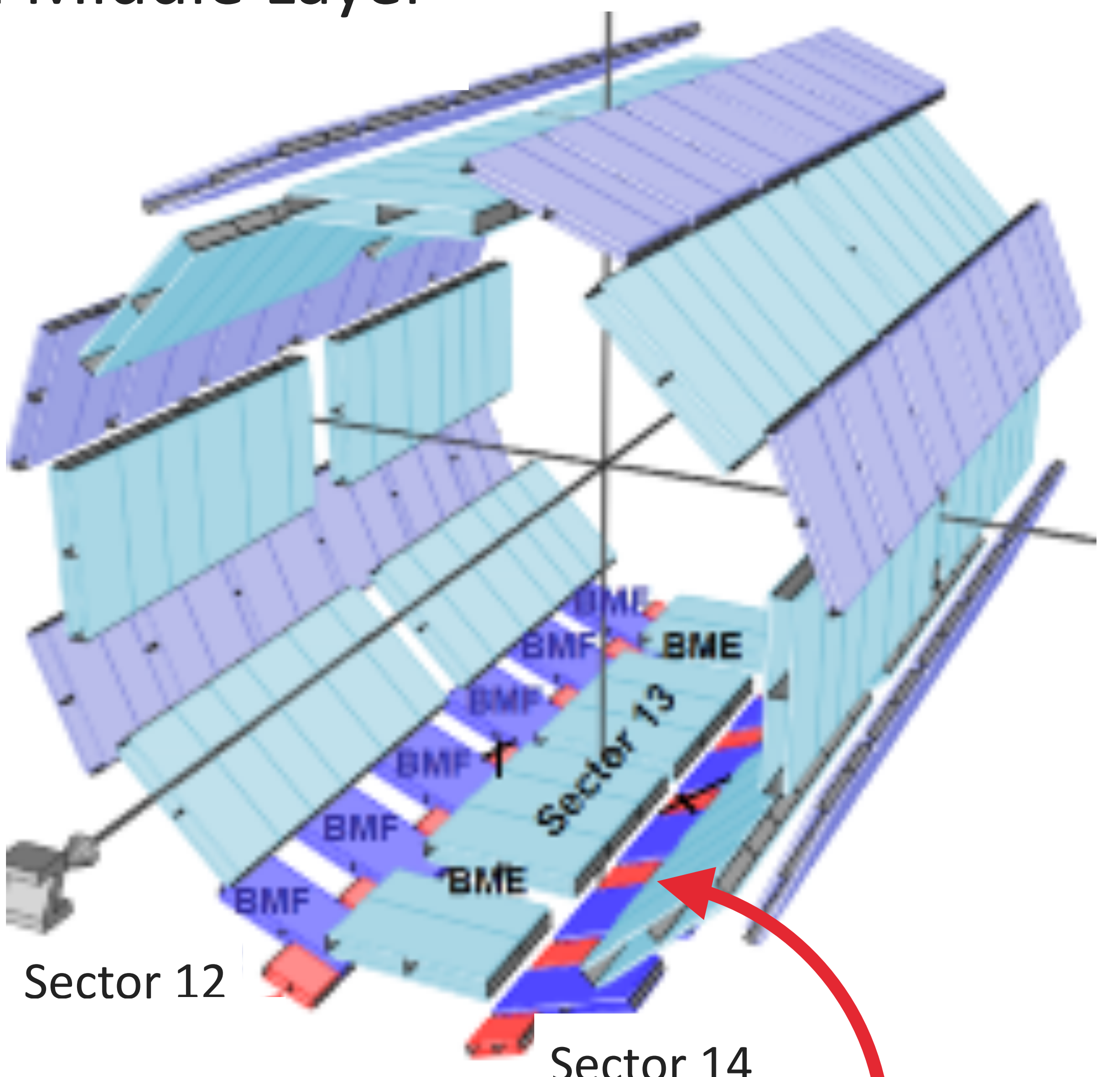
Need to upgrade the Small Wheel of Inner Endcap!

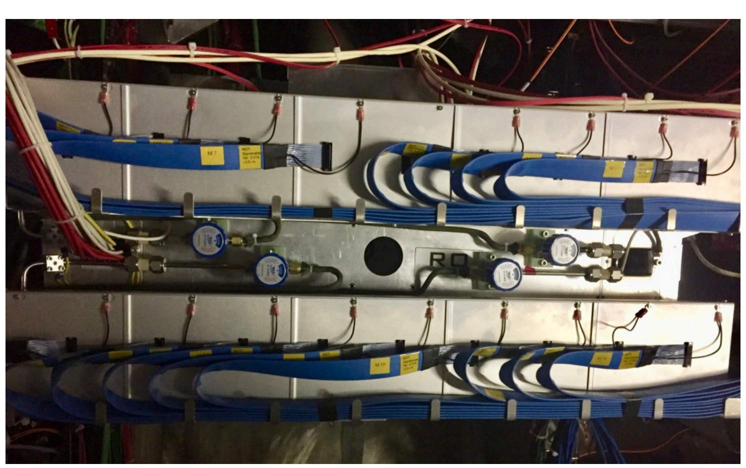
Consider two options for our "New Small Wheel"

1. small-MDTs
2. MicroMegas

small MDT Chambers

Barrel Middle Layer





BMG2C14

Proven technology:

several small MDT chambers already installed in ATLAS

Why they could be a solution

tubes 1/2 radius of regular MDTs

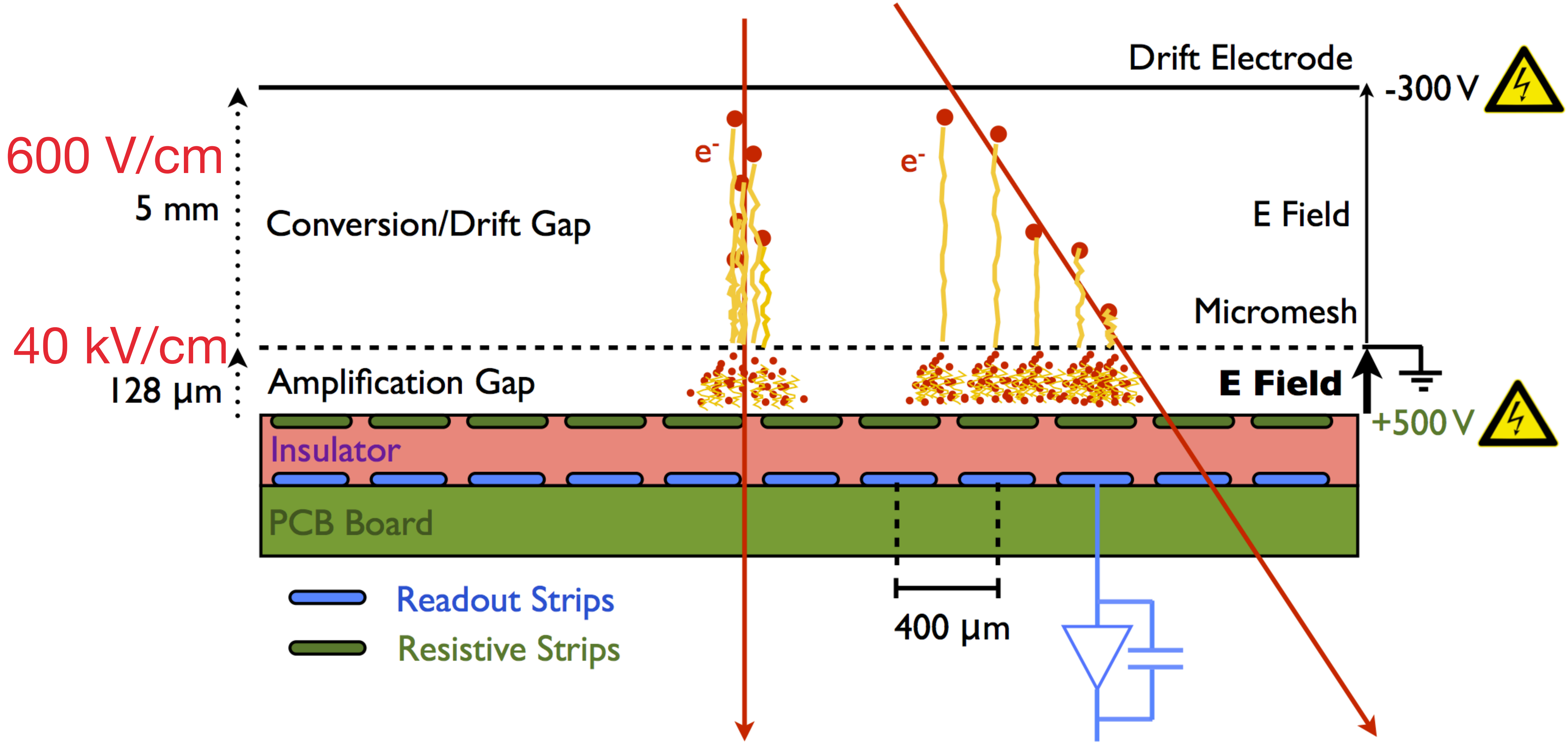
~8x better rate capability

max rate = 4 kHz/cm^2

At the HL-LHC

could replace Small Wheel MDTs but not the entire Small Wheel

MicroMegas Detectors



1. Small amplification gap

Fast movement and absorption of ions

→ 200 ns dead time/strip

2. Small strip pitch 425-450 µm

Maximum Rate

~1 / (dead time * strip area)

~1 MHz / cm^2

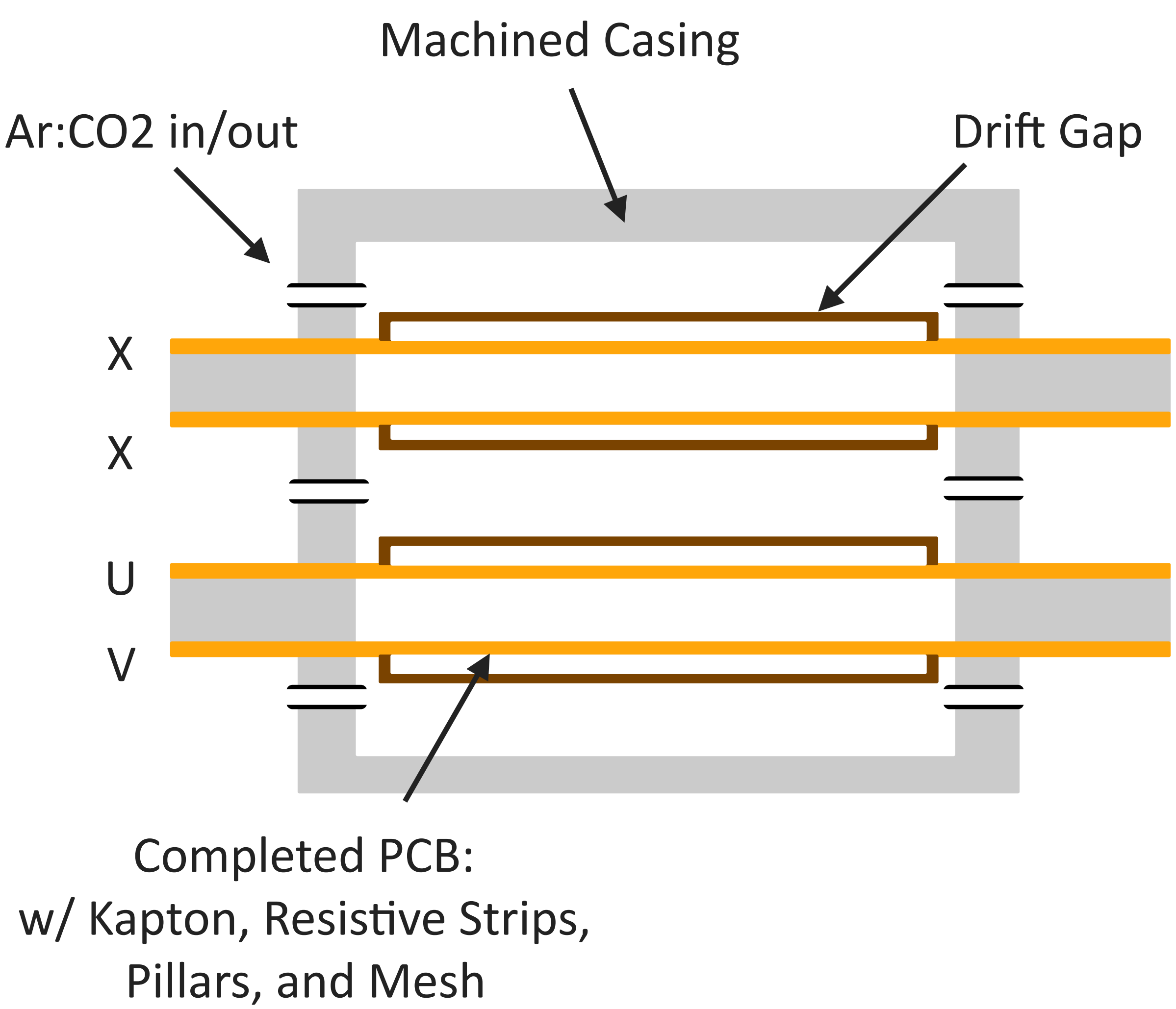
can replace entire small wheel!

Building a MM octuplet at Harvard

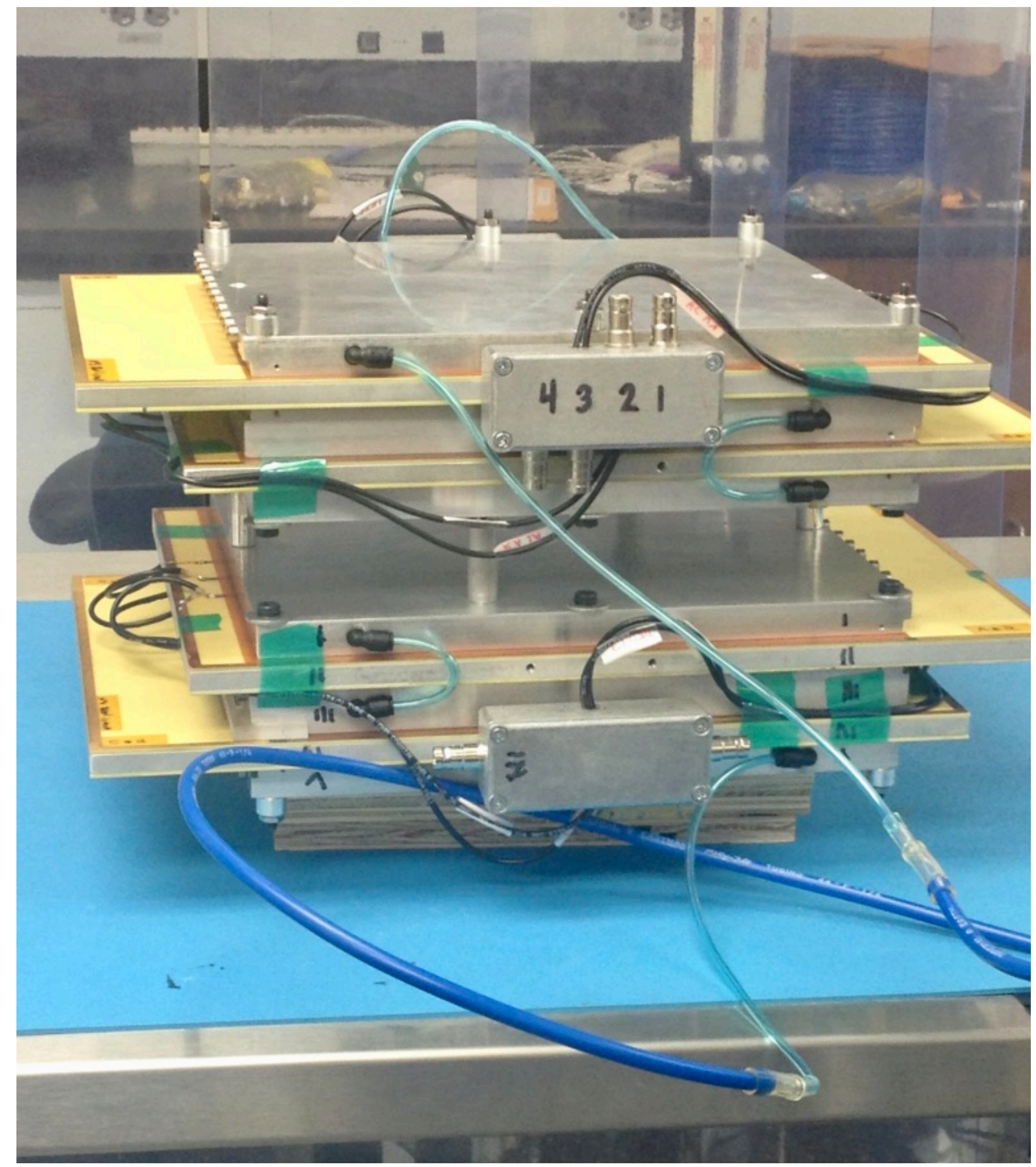
Quadruplet Design

Octuplet consists of 2 Quadruplets

20x20 cm chambers

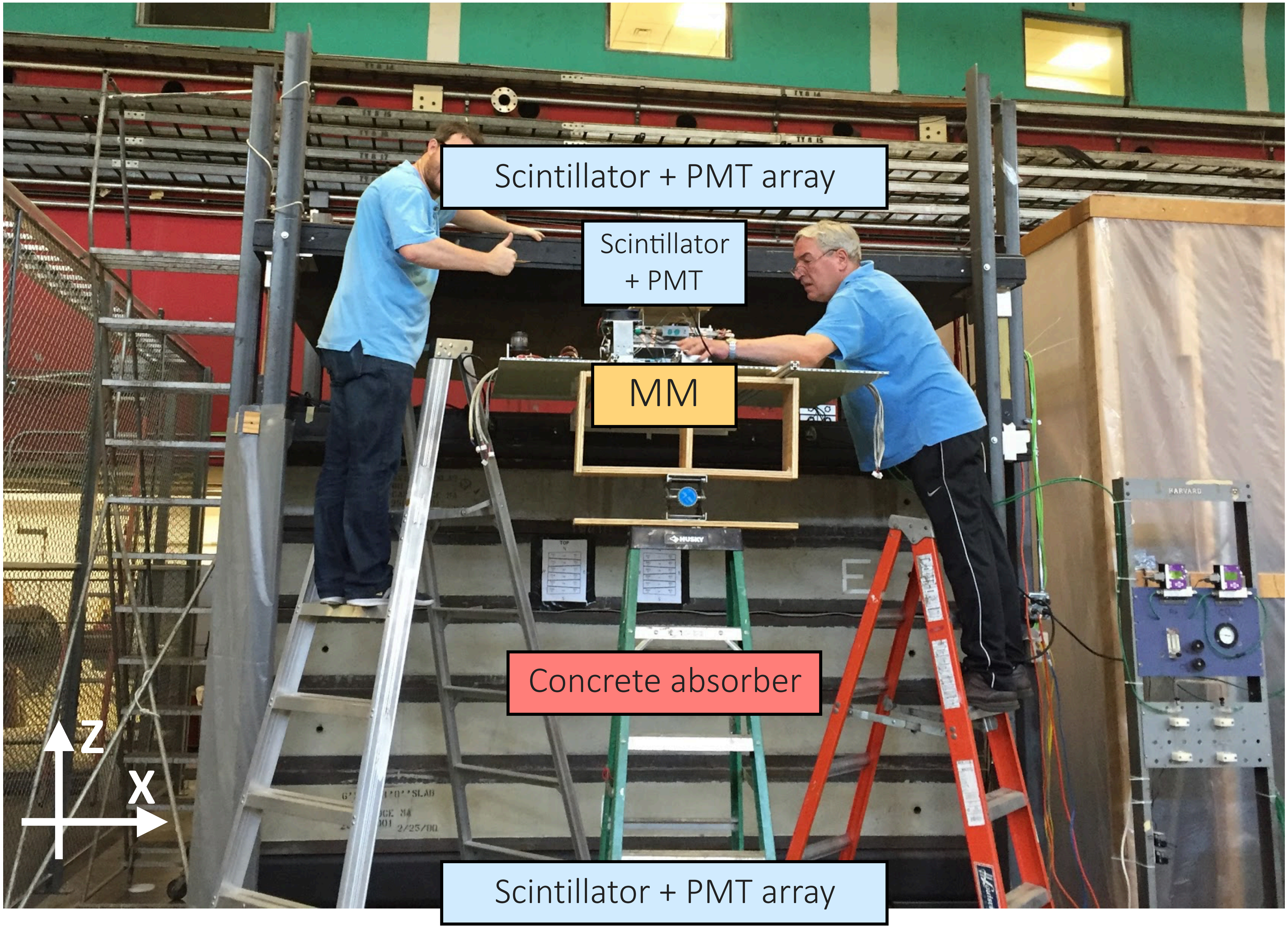


U strips angled at + 1.5˚
V strips angled at - 1.5˚



Cosmic Ray Test Stand

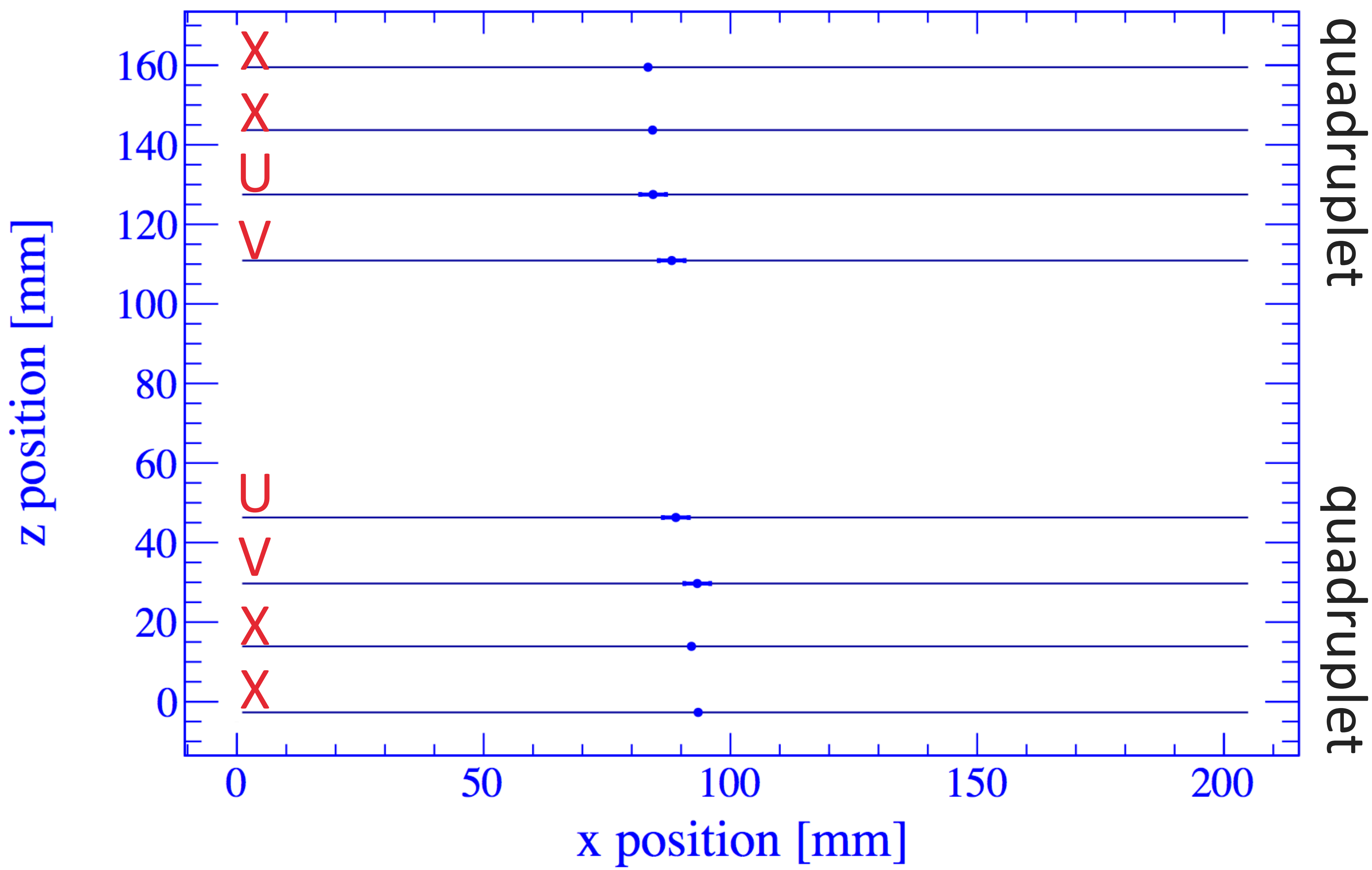
Cosmic Ray Test Stand



Success!

Collected millions of cosmic muon events between 2016-2018

many useful studies of detector and electronics performance
with a particular focus on testing full trigger path



Many lessons learned along the way

Building MicroMegas detectors is challenging

very sensitive to cleaning procedures, sparking, and noise

ATLAS also dealing with these challenges

working very hard on MicroMegas production
for New Small Wheel installation before 2021

Conclusions

Looking forward to hunting for signs of new physics in Run 2 & 3 and preparing ATLAS detector for future data-taking

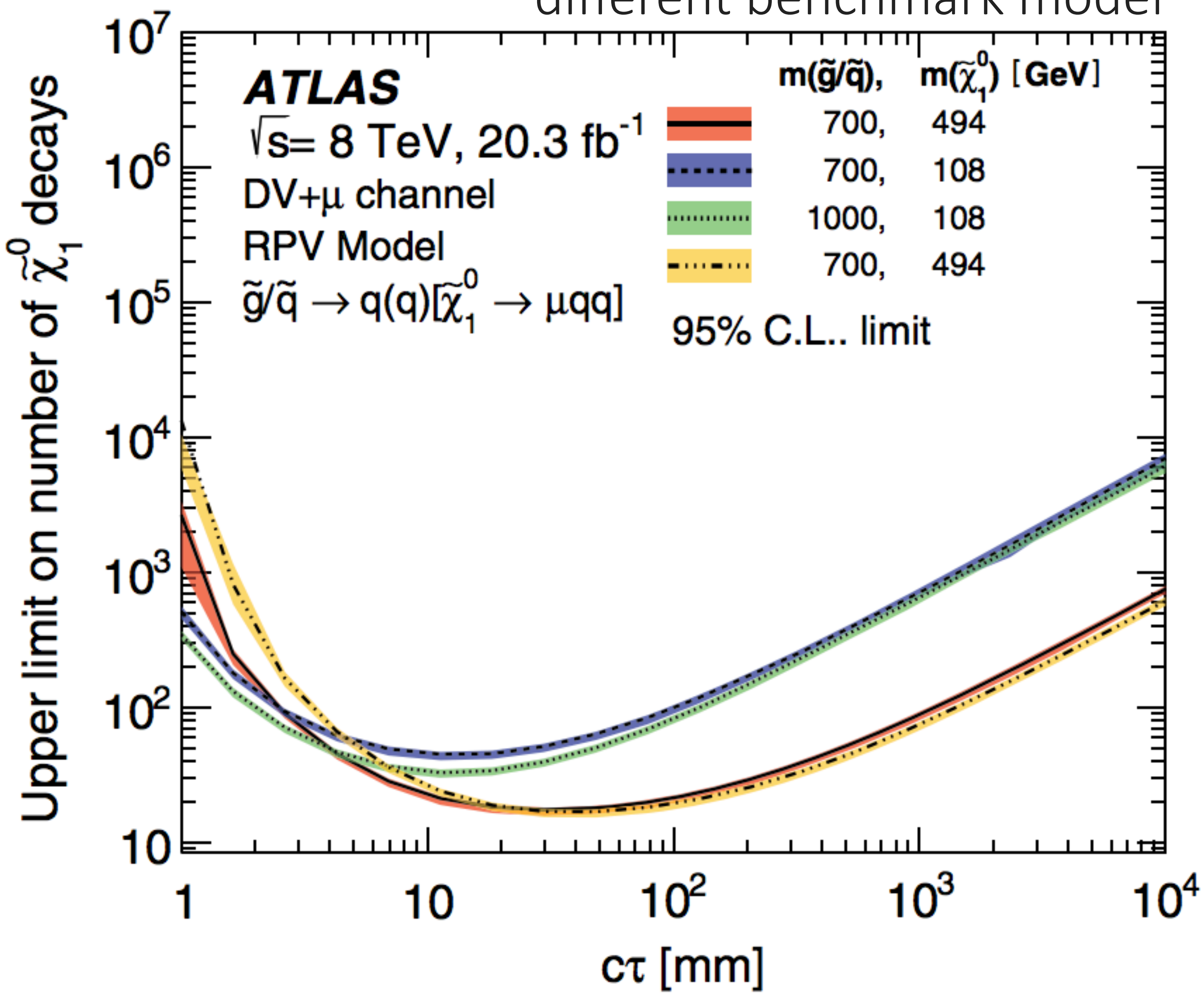
And special thanks to

DV+muon: Lawrence Lee Jr., Melissa Franklin, and SUSY DV Team

Muon Spectrometer: Alex Tuna, Siyuan Sun, Tony Tong, Ann Wang, Tomo Lazovich, Chris Rogan, Melissa Franklin, Paolo Giromini, Tiesheng Dai, Zhen Yan, and Philipp Fleischmann

Run 1 ATLAS Results

different benchmark model



Best sensitivity

~20% signal acceptance x efficiency

for t->q+μ at at 0.1 ns

excludes stops up to 1 TeV

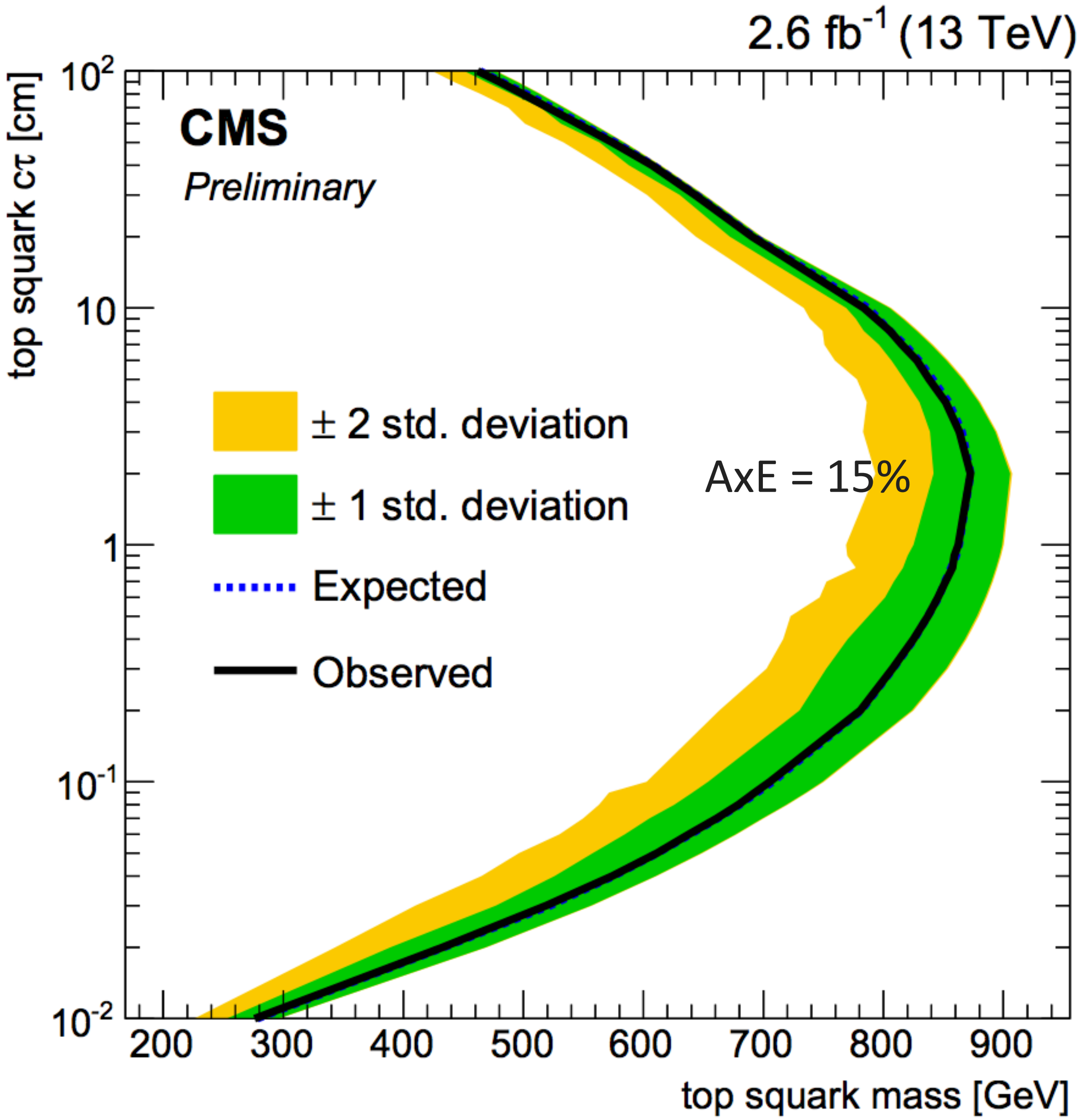
PhysRevD.92.072004

Related CMS Analyses

Displaced Leptons, eμ

probes two λ' couplings

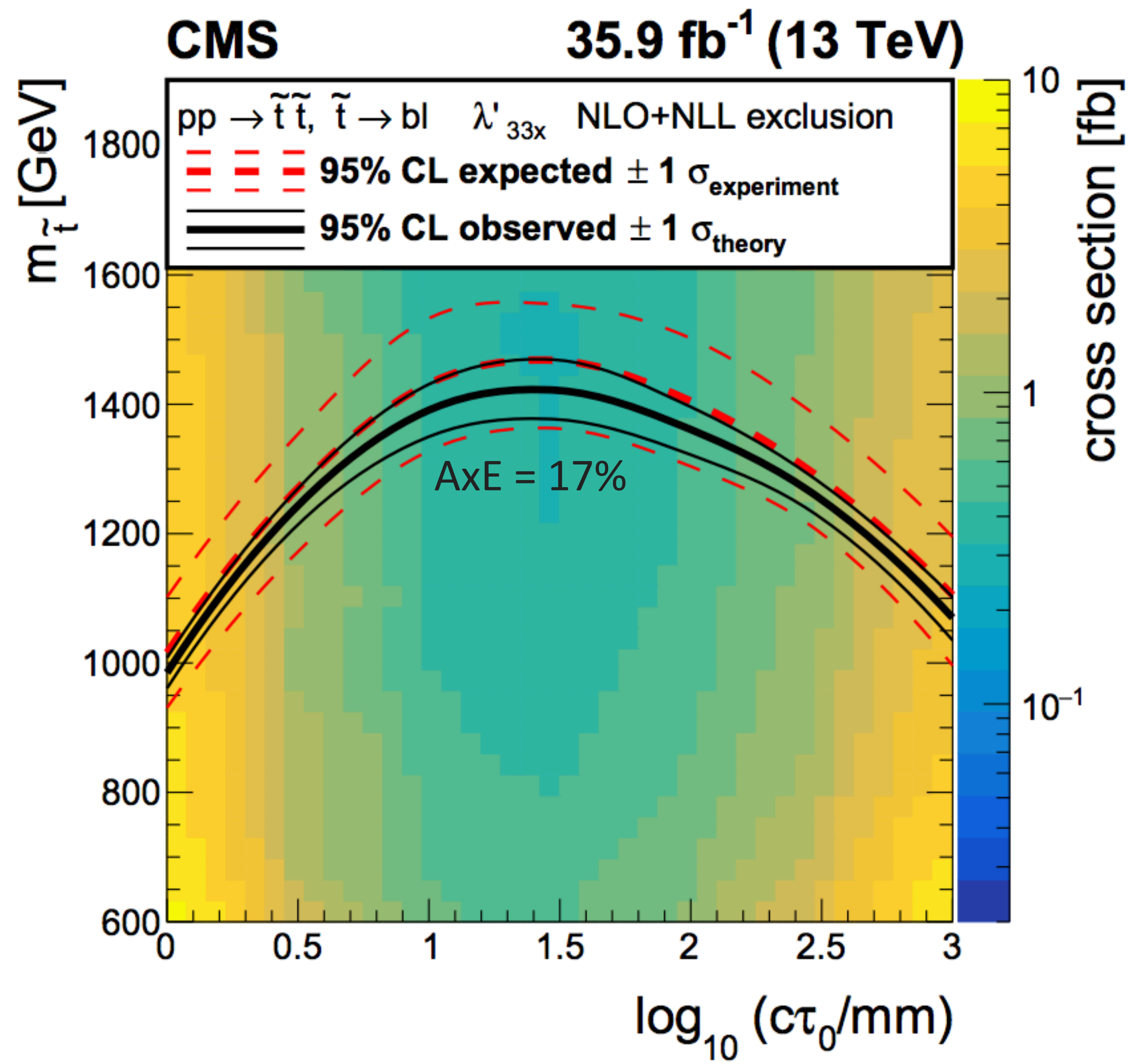
850 TeV stops at $\tau \approx 0.1$ ns, 2.6 fb^{-1}



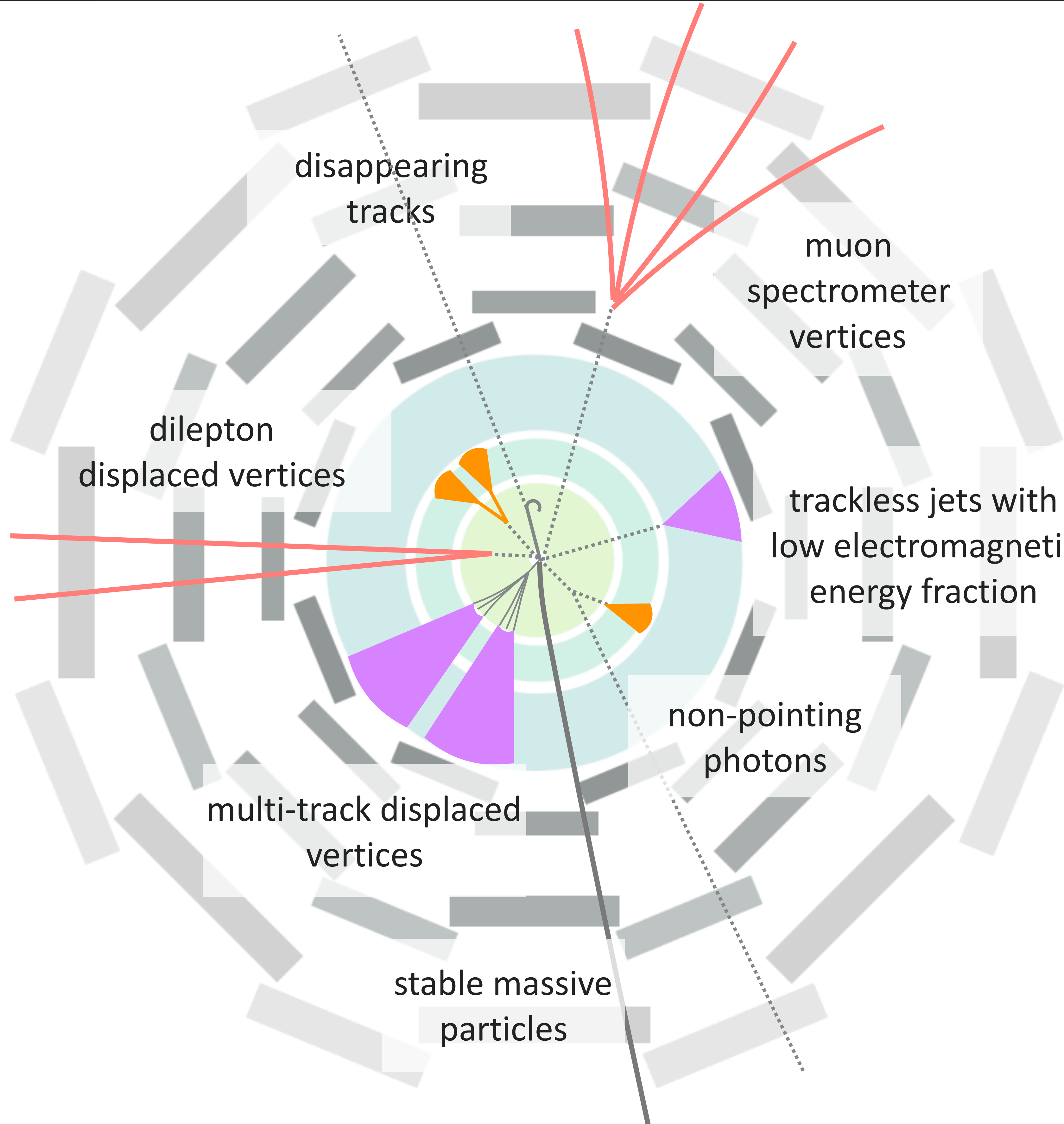
Displaced Jets

jets need not be from the same vertex

best: 1.4 TeV stops at $\tau \approx 0.1$ ns, 35.9 fb^{-1}



Long-lived particle searches in ATLAS



ATLAS Trigger Reminder

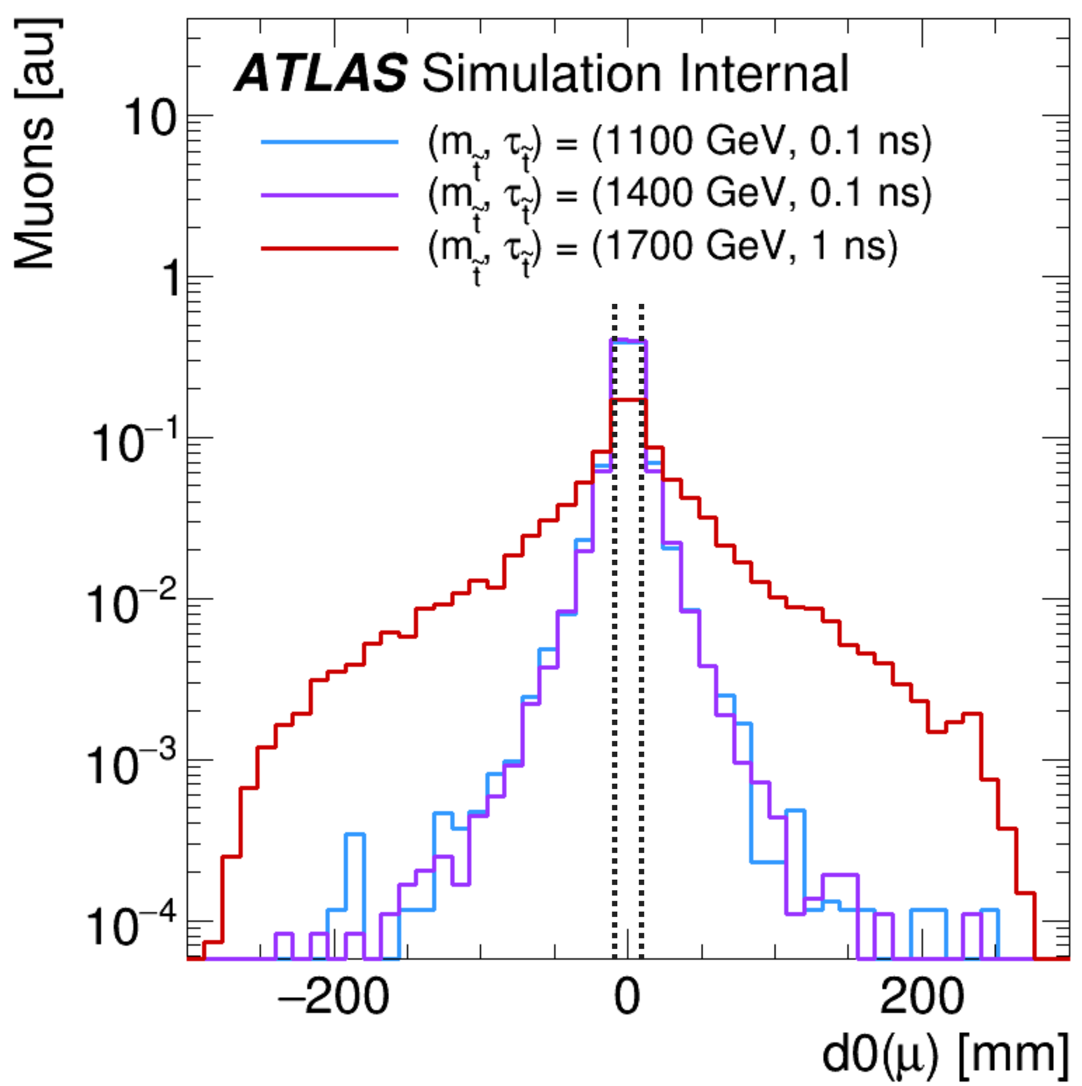
Level 1 Trigger uses Calorimeter & Muon Spectrometer information
cannot trigger on inner detector displaced vertices in ATLAS

Standard muon triggers

Require a Muon Track
matched to an Inner Detector Track

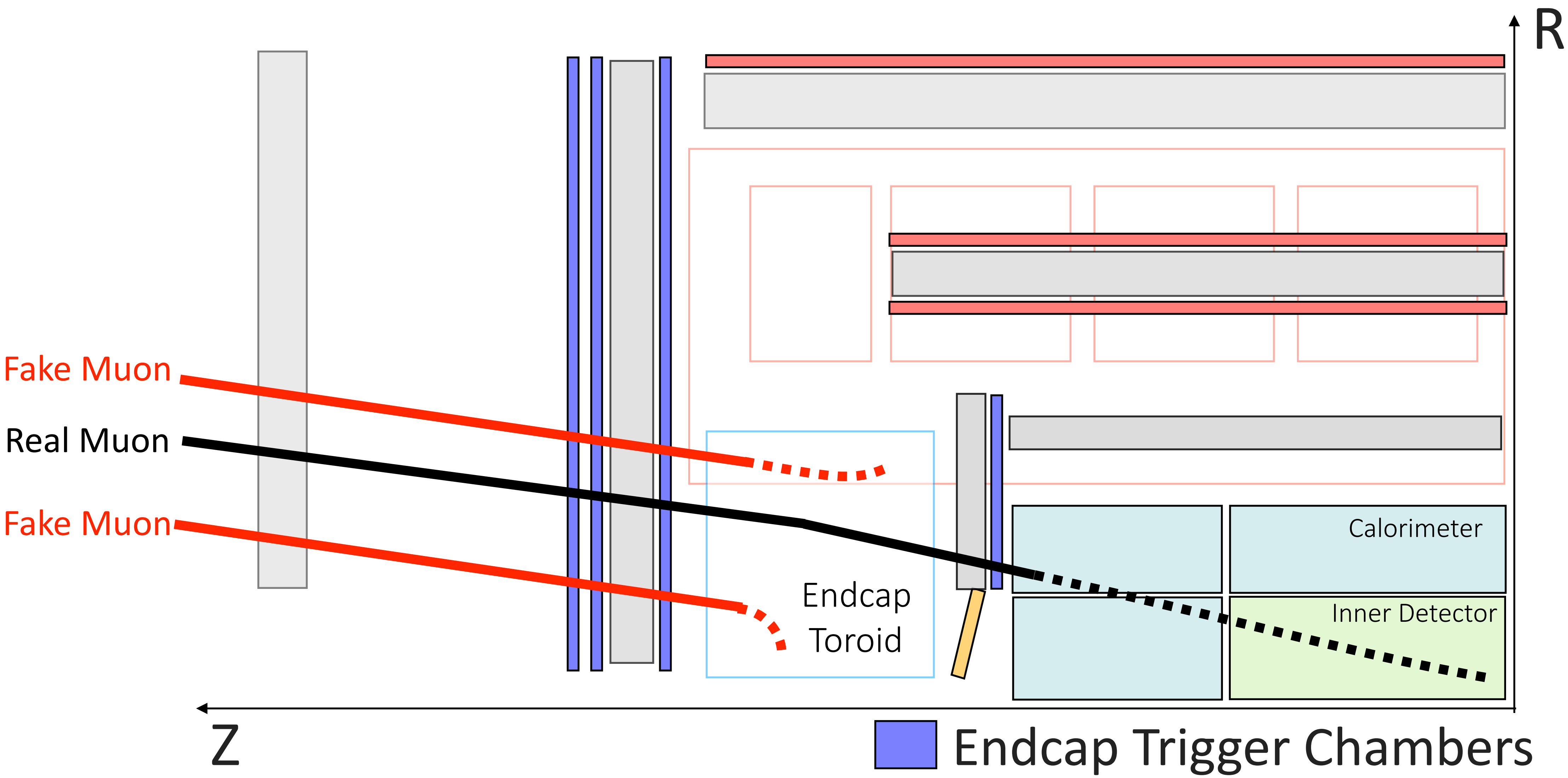
Strict impact parameter requirements
|d0| < 10 mm

Inefficient for signal!



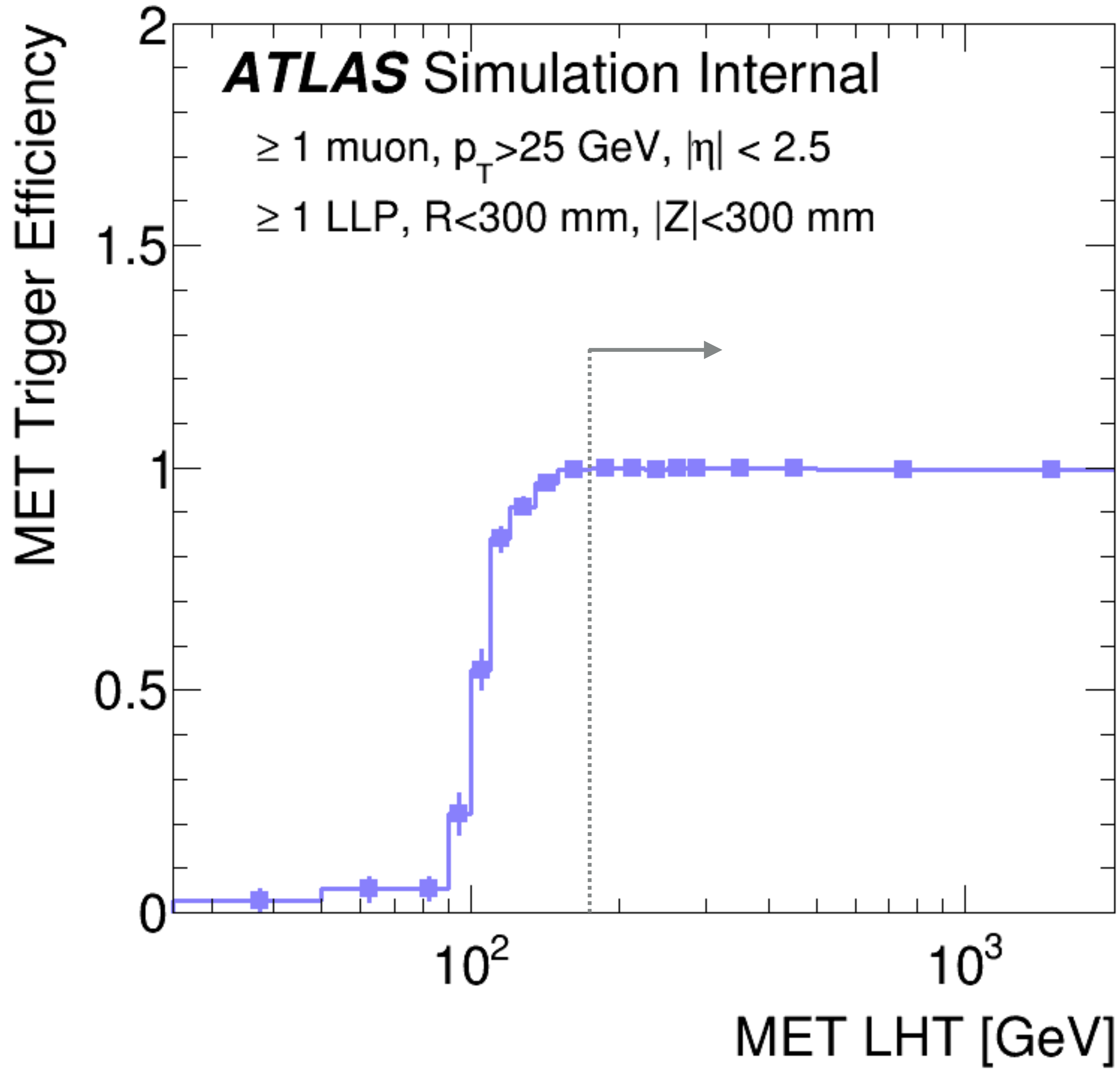
Muon Spectrometer Only Trigger Backgrounds

cannot use Endcaps because of large background rate



*Note: limited trigger coverage in the Inner Endcap

MET Trigger Turn on

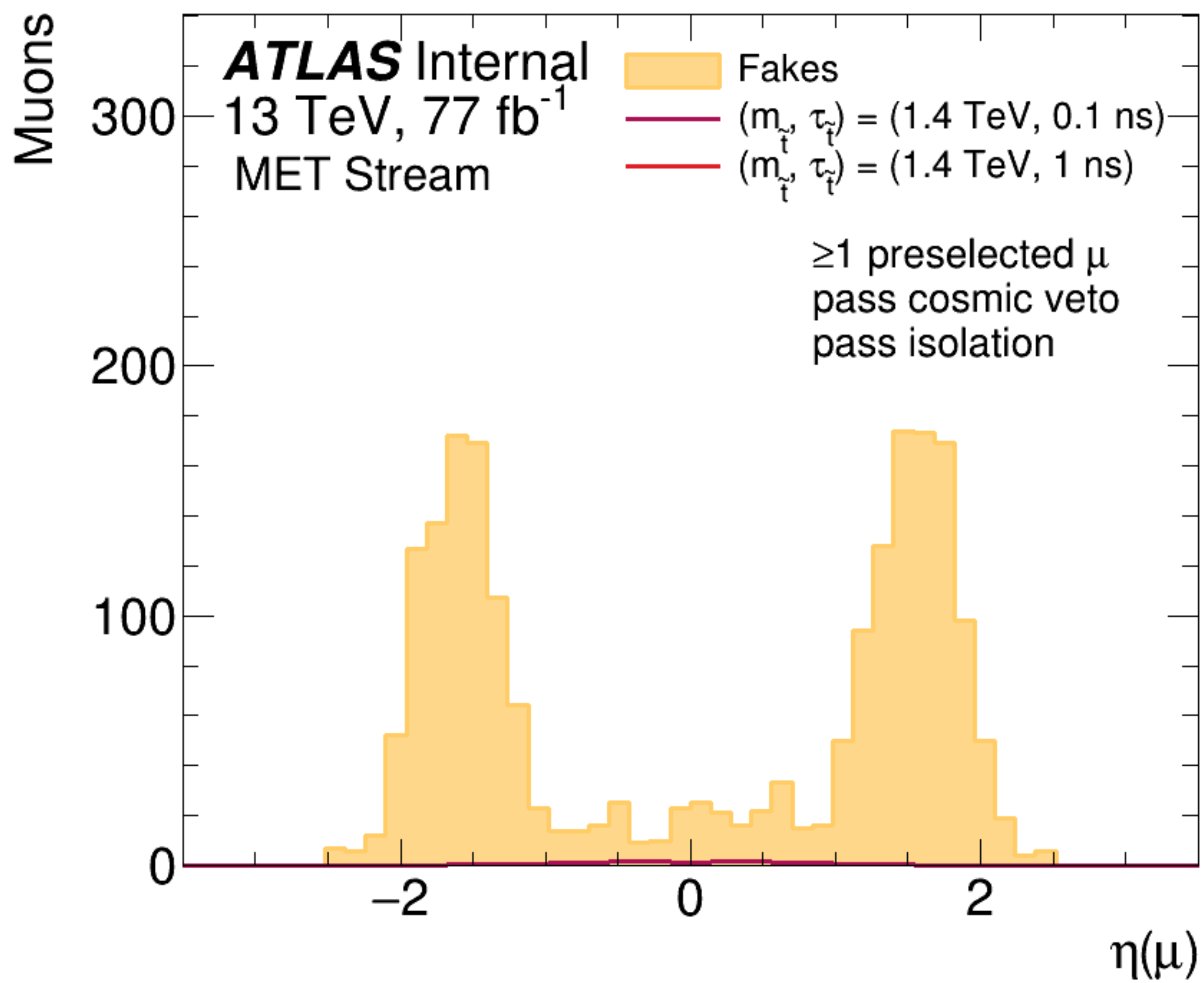


Algorithm Fakes

Large background in MET triggered events

fake inner detector track matched to fake muon spectrometer track

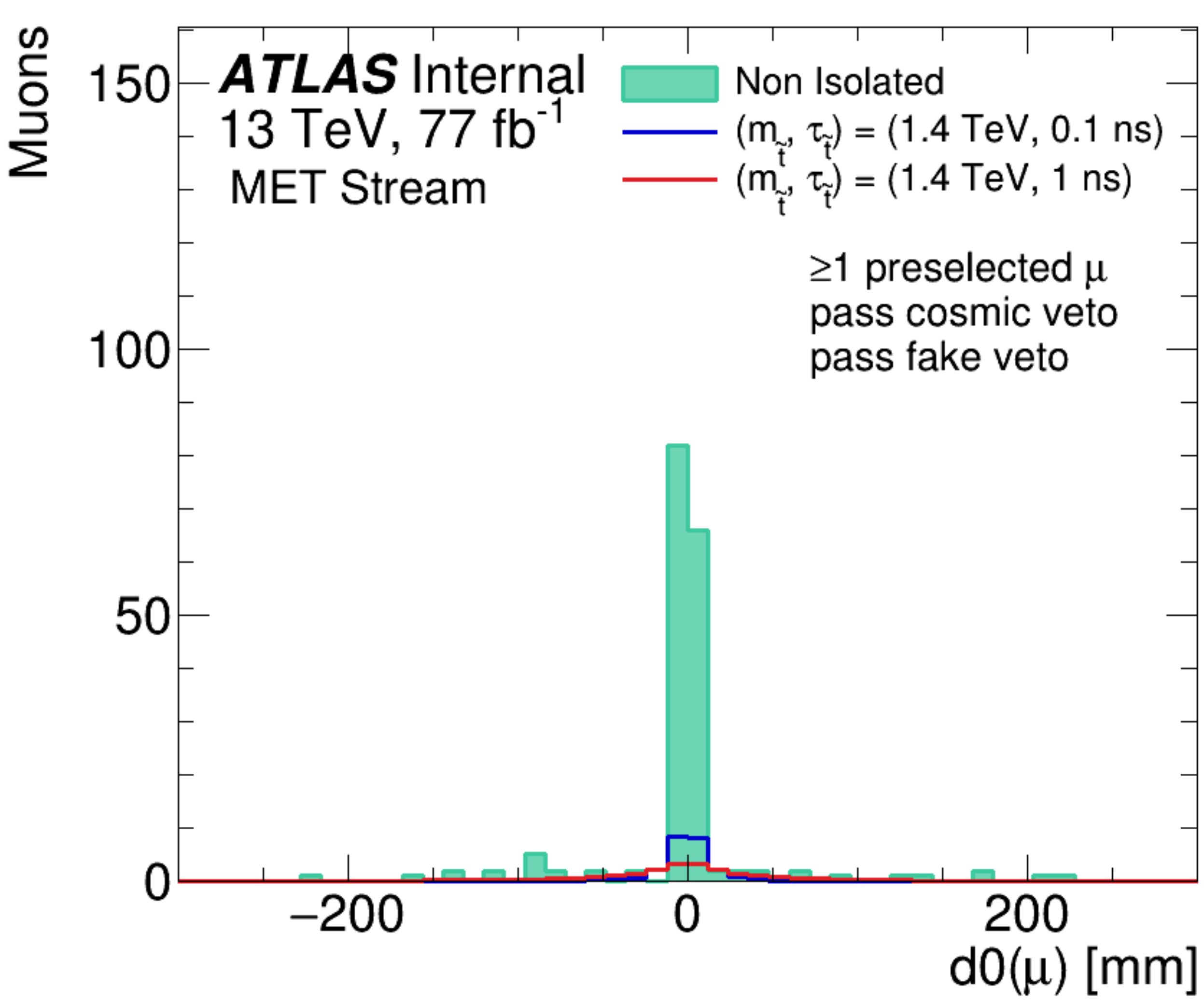
mostly affects endcaps

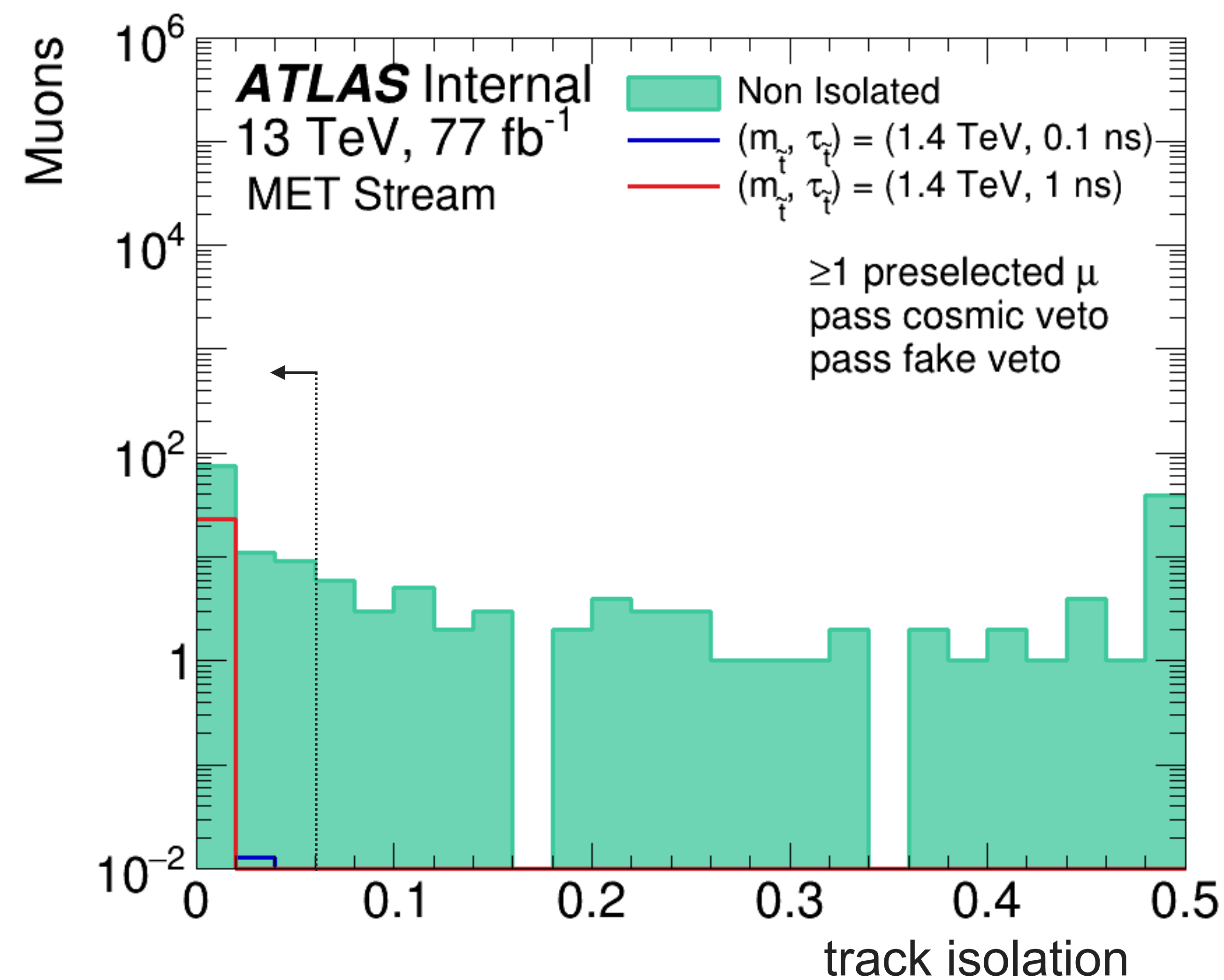


Heavy Flavor Muons

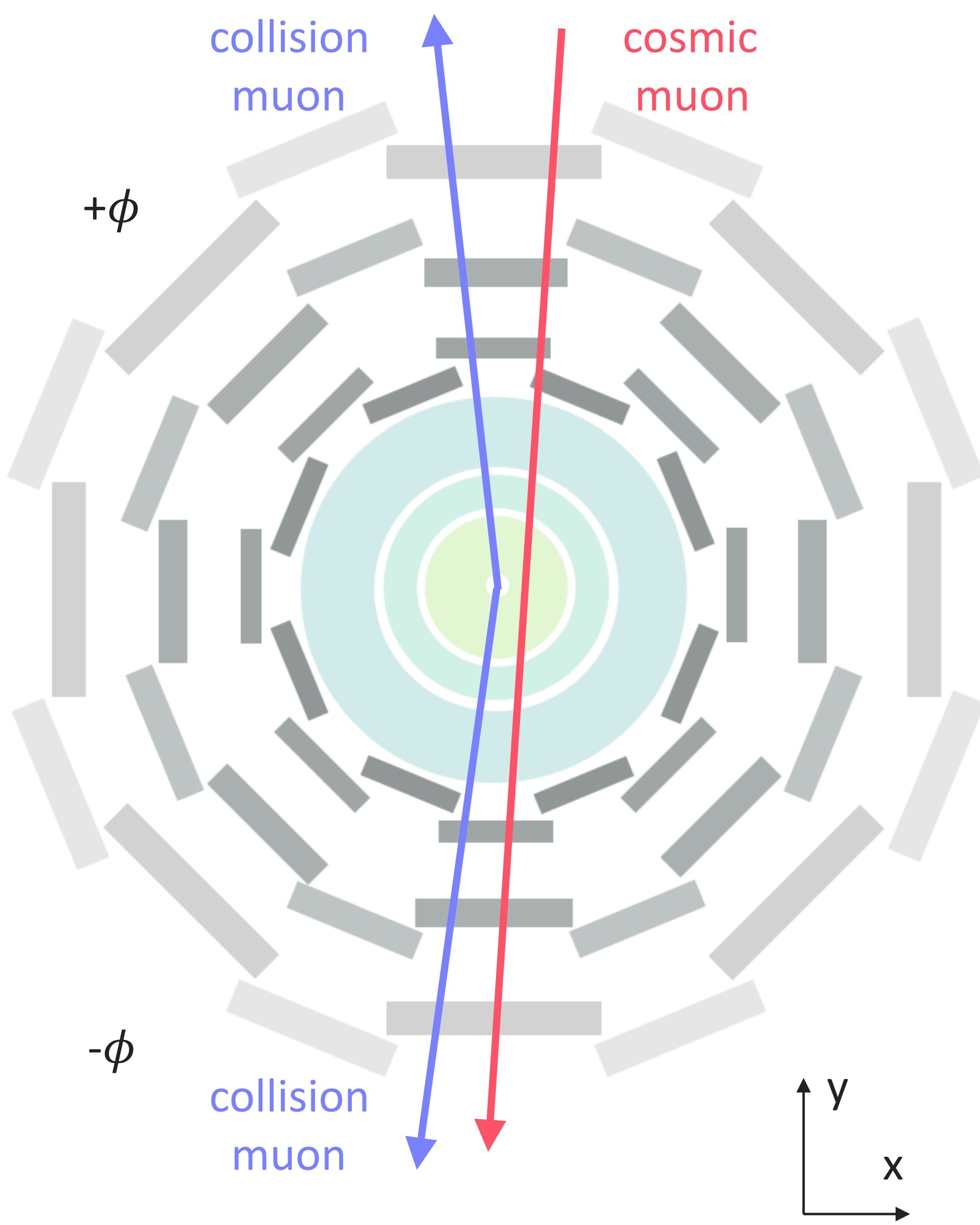
tend to have small impact parameters

also shown, track isolation





Cosmic Muons



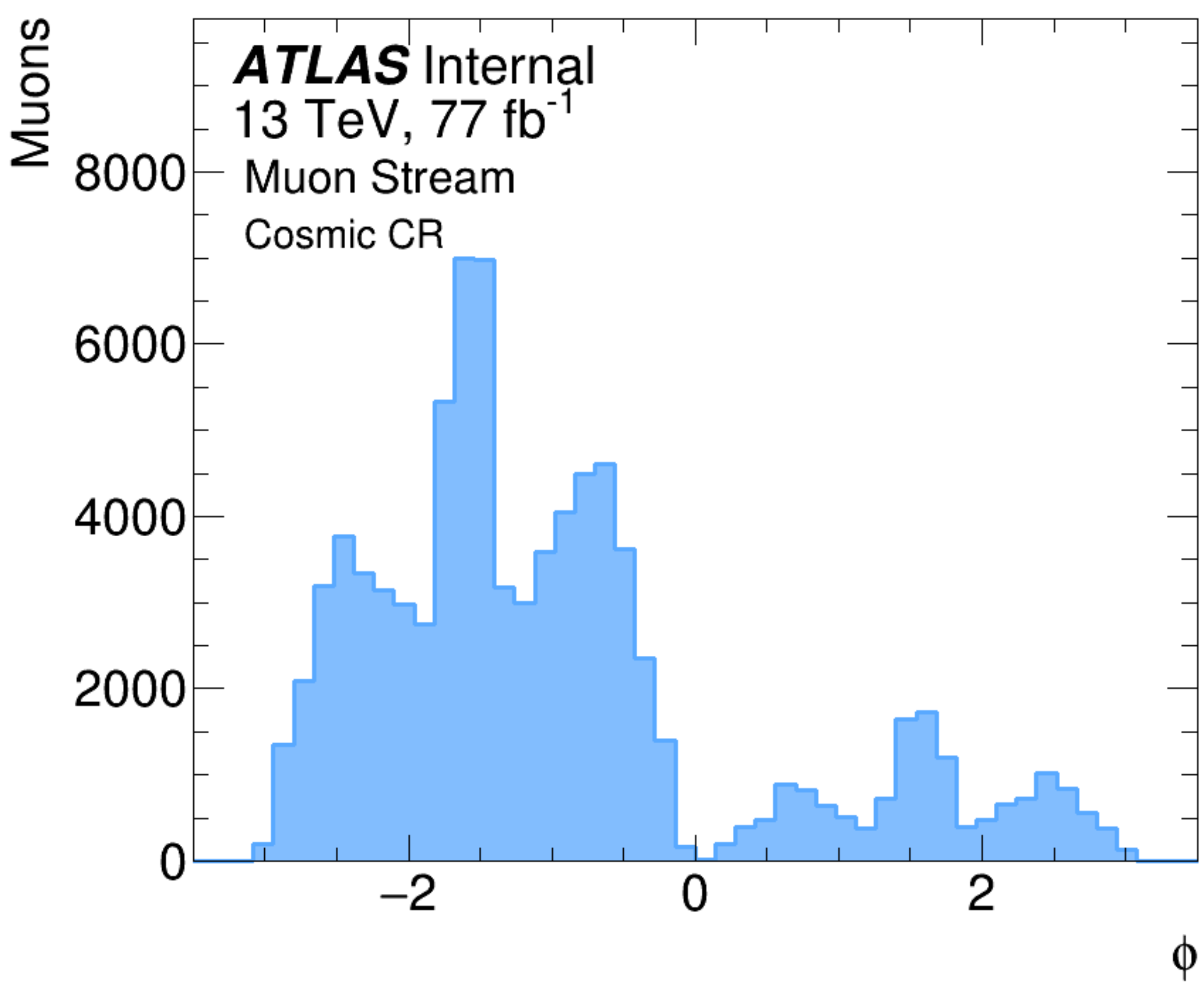
$+\phi$ muon timing difference with respect to collision muons

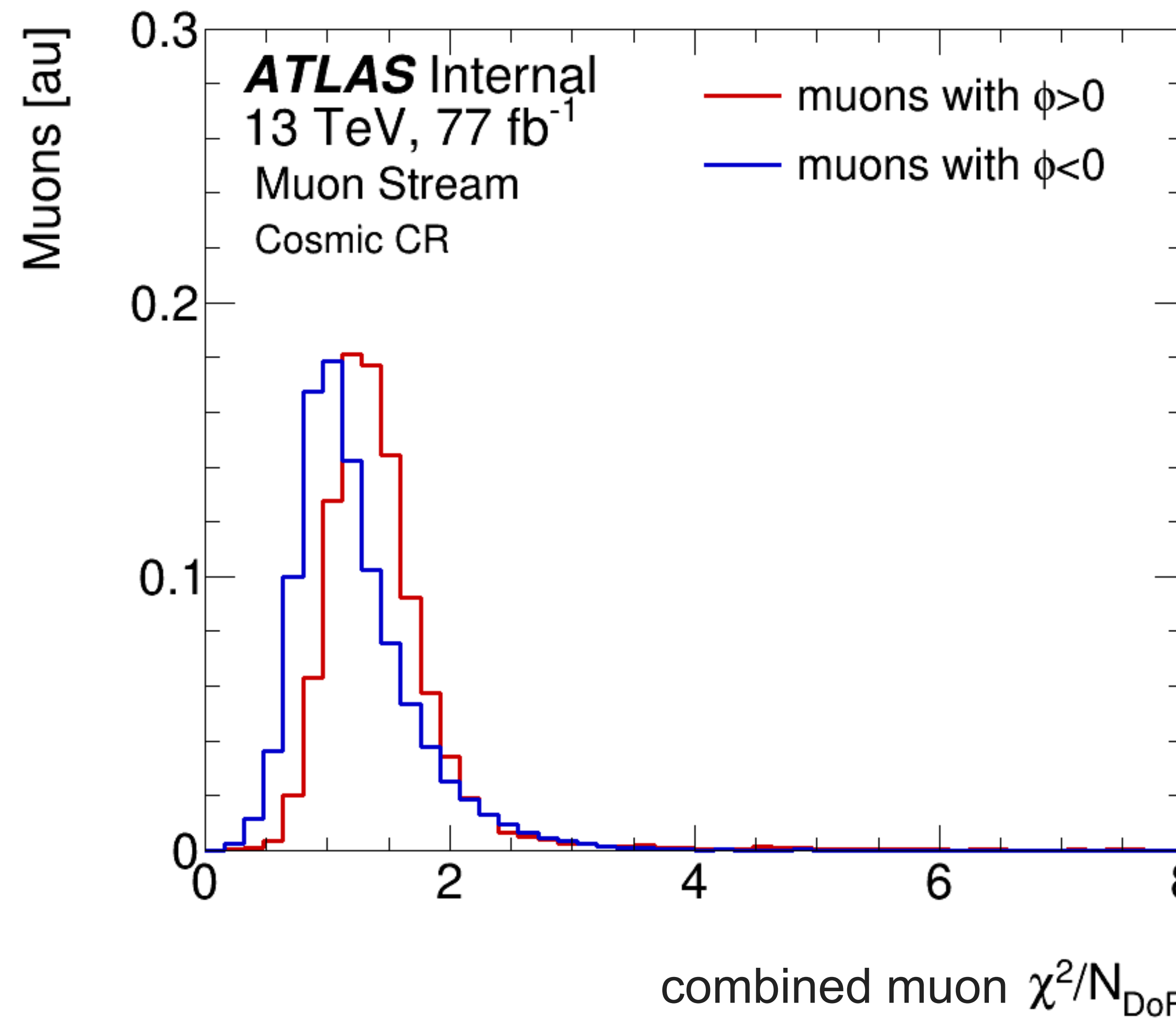
Muon Station	R [m]	Δt
Inner	5	-33 ns
Middle	7.5	-50 ns
Outer	10	-67 ns

*if $-\phi$ muon is in time with collisions

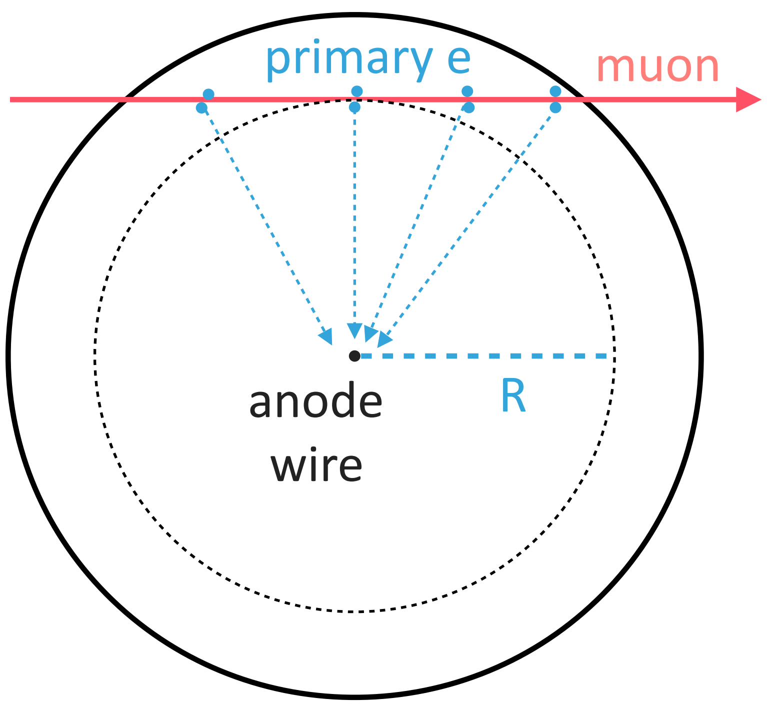
Cosmic Muon Properties

positive phi cosmic legs often aren't reconstructed as muons
when they are reconstructed, the tend have fewer hits on track,
and poorer fit quality

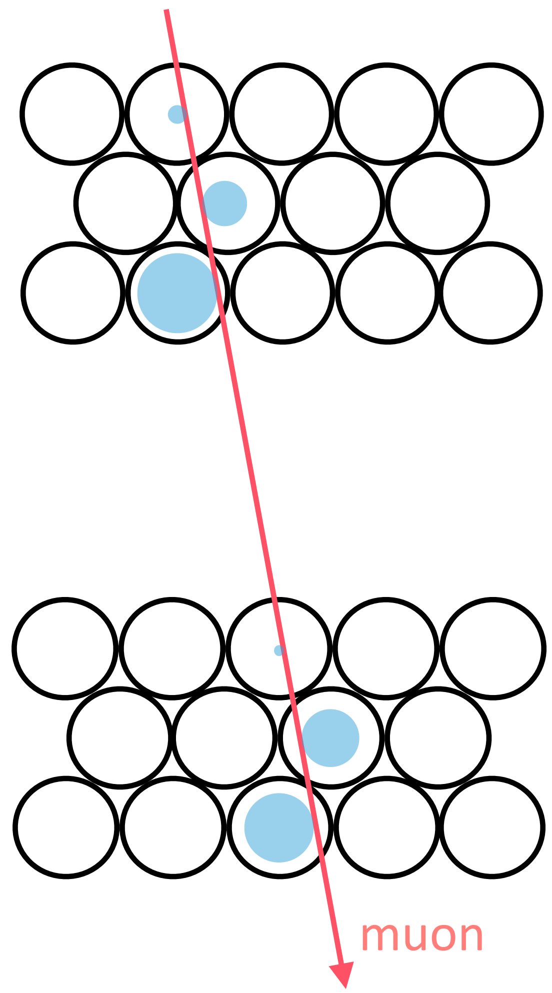




why timing affects quality of fit in monitored drift tubes



cathode tube
3 cm diameter



muon passing through
MDT chamber

if timing assumptions
are incorrect
eg. time of flight

measured hit positions
are incorrect

→ poorly fit muons

Geometric Correction

muon η measured at impact parameter

segment η measured w.r.t origin

Goal: correct muon η to detector η

such that ηcorr(μ)+ η(seg) = 0

Step 1: find correct Z(R,z0)

Zcorr = Zμ(R) - z0

tan (θμ) = R segment / z muon

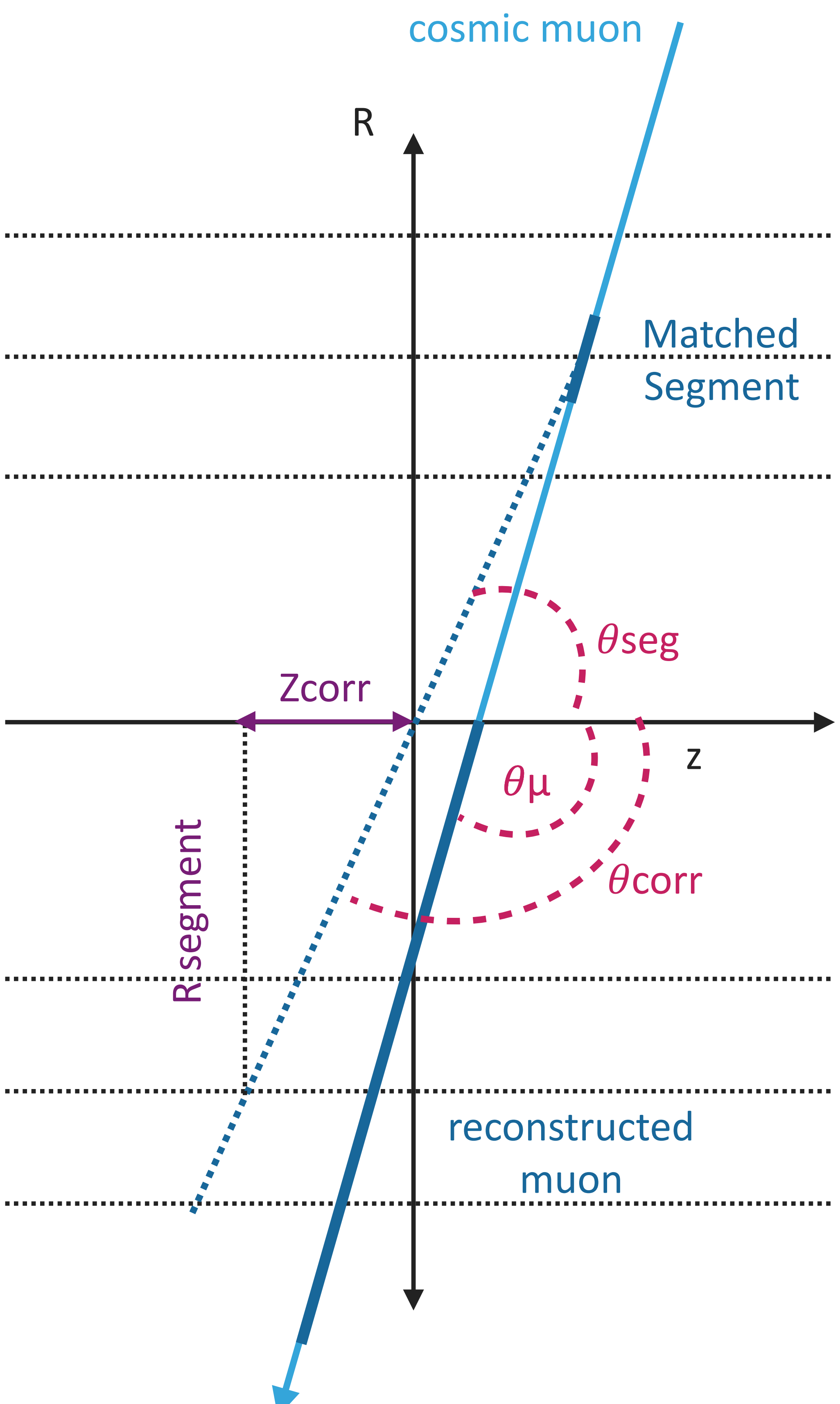
gives you

Zcorr = R segment / tan (θμ) - z0

Step 2: convert Z to η(R,z0)

θcorr = arctan (R segment / Zcorr)

ηcorr = -ln(tan(θseg/2))



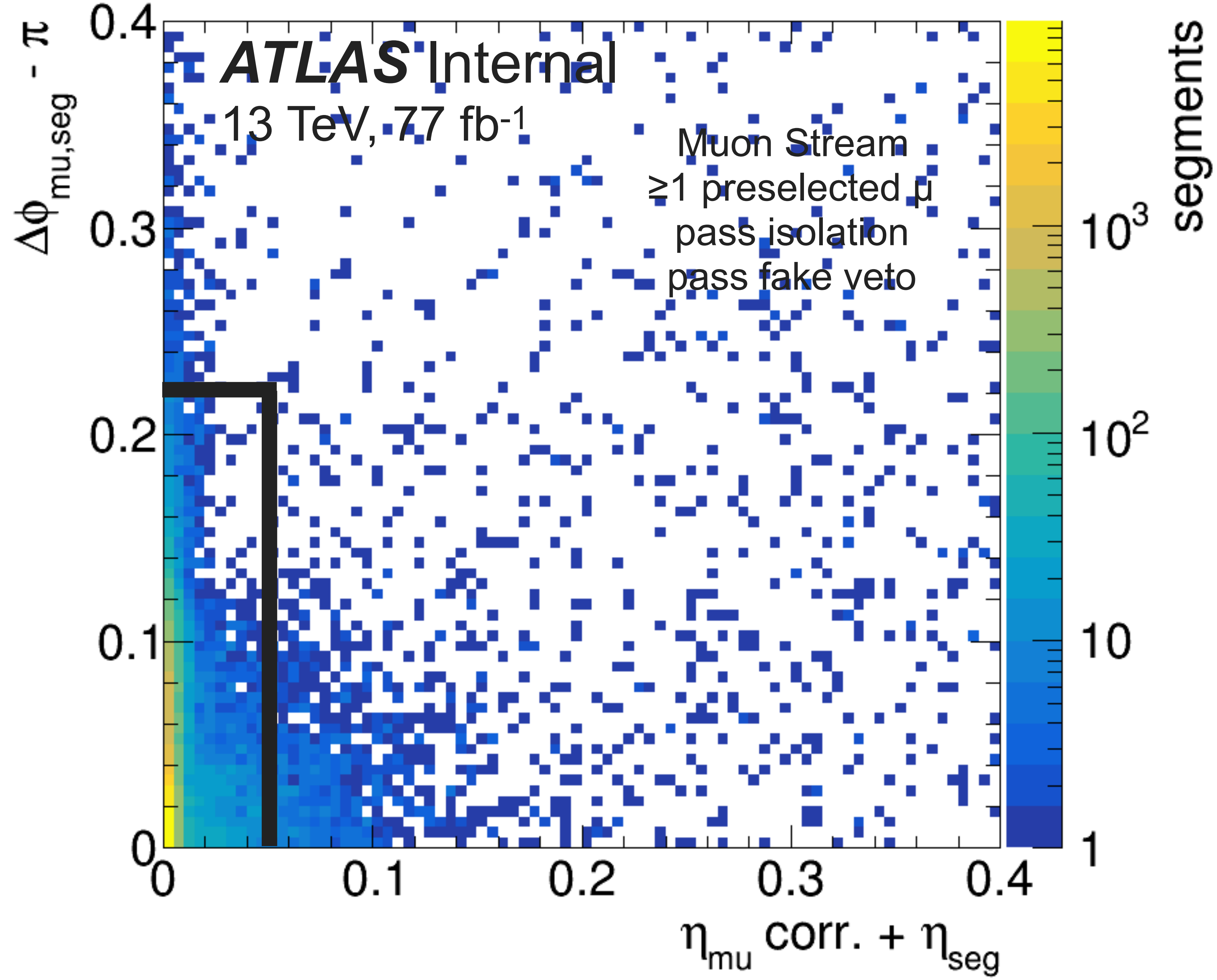
Cosmic Veto - in 2 dimensions

Sum η_{corr} < 0.05

roughly size of a few tubes

$\Delta\phi - \pi < 0.22$

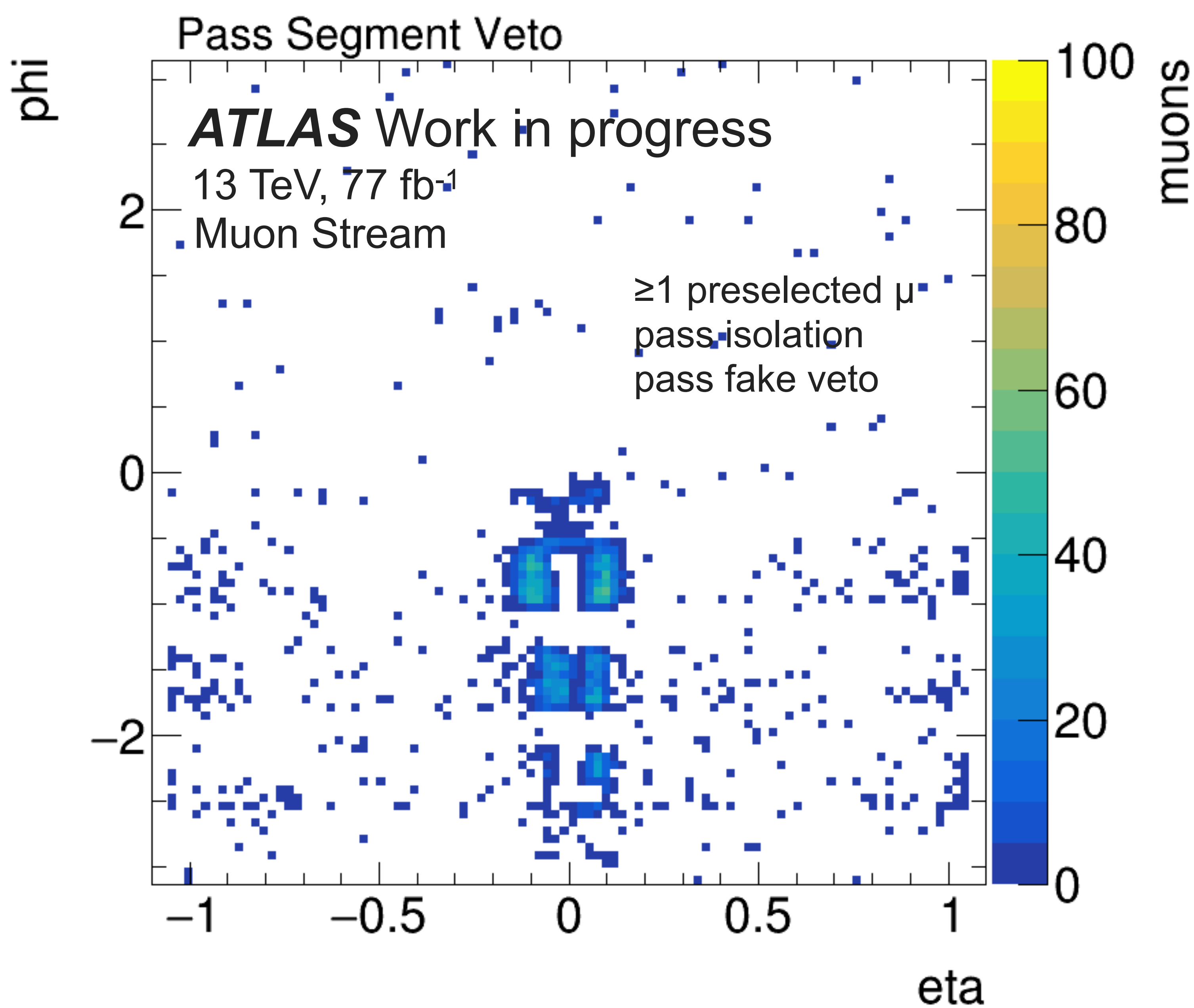
roughly size of 1 MDT chamber in phi



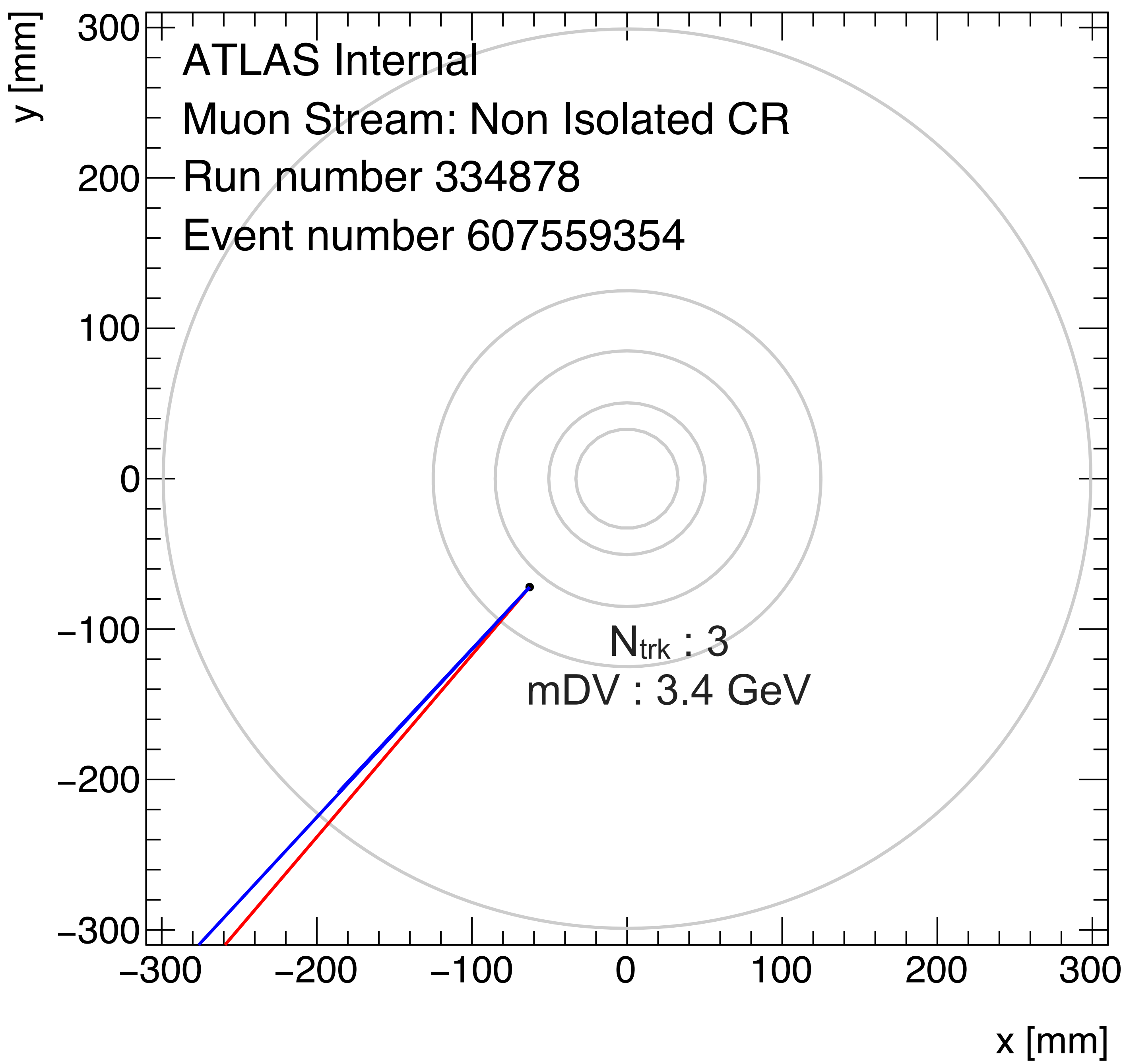
Cosmic Veto

Cosmics which pass the back-to-back segment veto form interesting pattern in eta-phi

Near eta = 0, and in large sectors



What do displaced vertices in data look like?



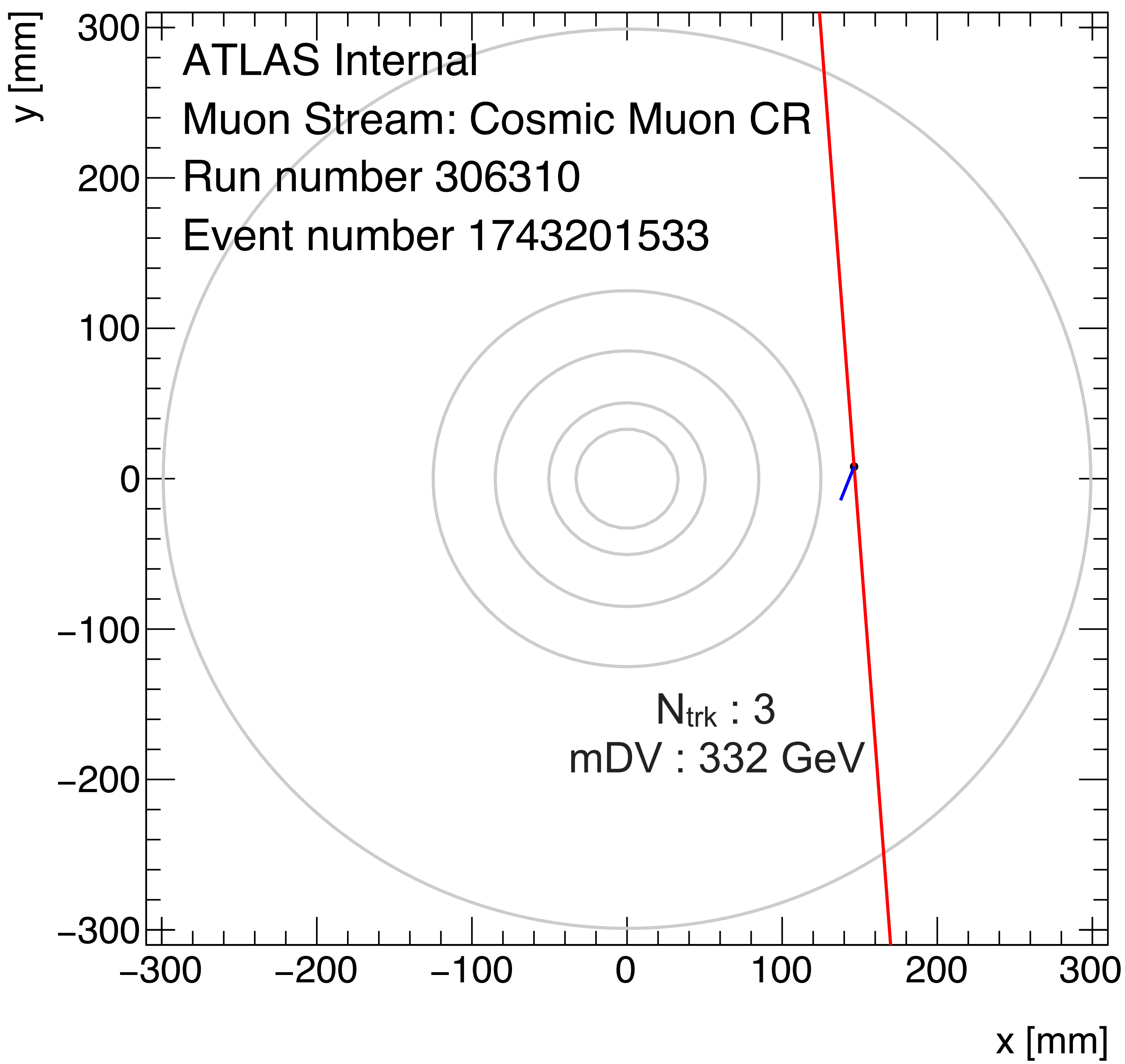
A little more rare

in non-isolated control region material interactions from high momentum jets

low mass vertices, but with high momentum and highly collimated tracks

muons sometimes reconstructed as part of the vertex

What do displaced vertices in data look like?



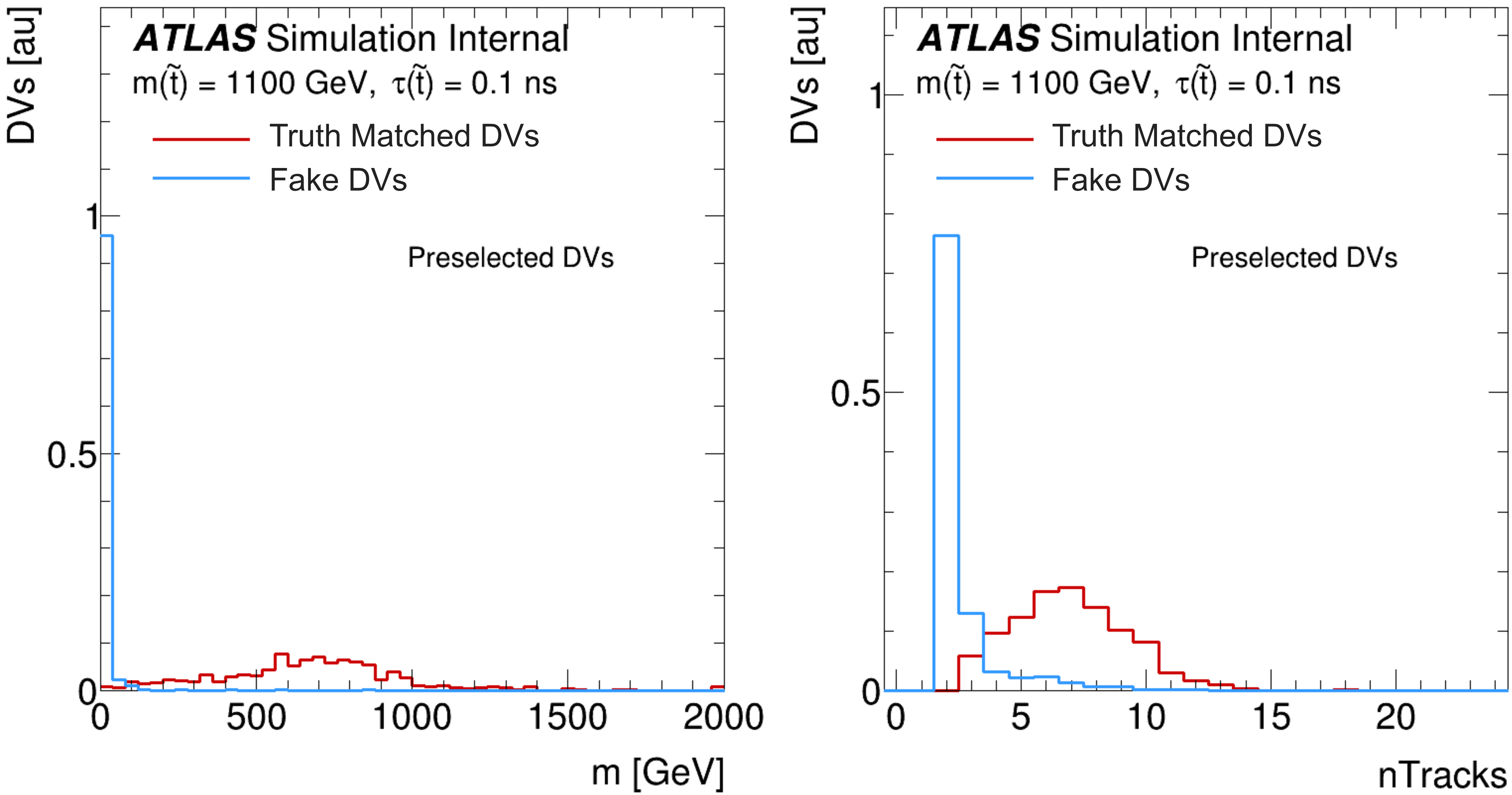
Cosmic vertices

most often two back-to-back high momentum tracks from cosmic

sometimes an additional crossing 3rd track - very rare!

form very high mass displaced vertices

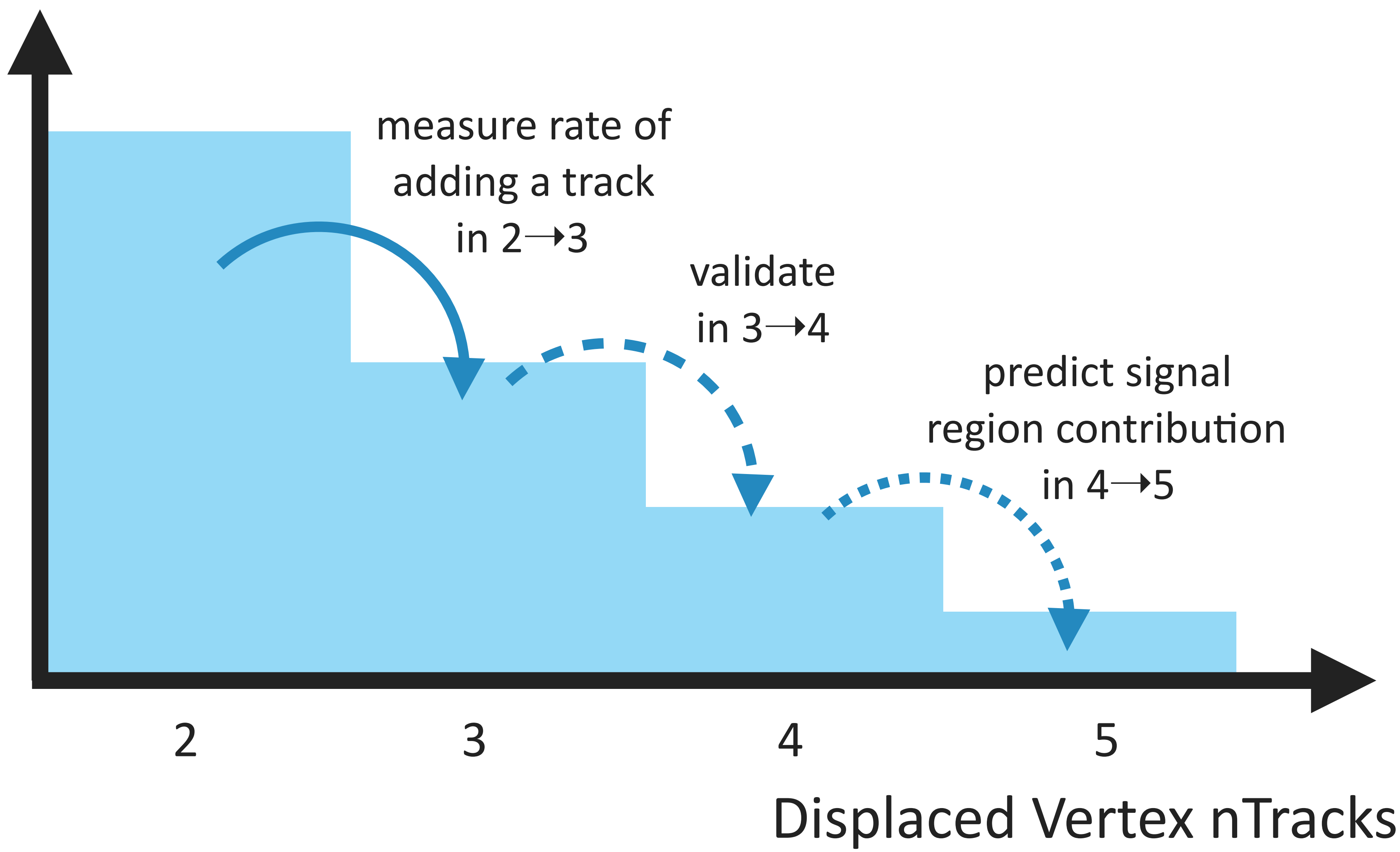
Displaced Vertex Selection



Run 1 Background Estimation Strategy

In Run 1

backgrounds were estimated using displaced vertex properties
eg. random track crossings



requires cutting on DV nTracks ≥ 5

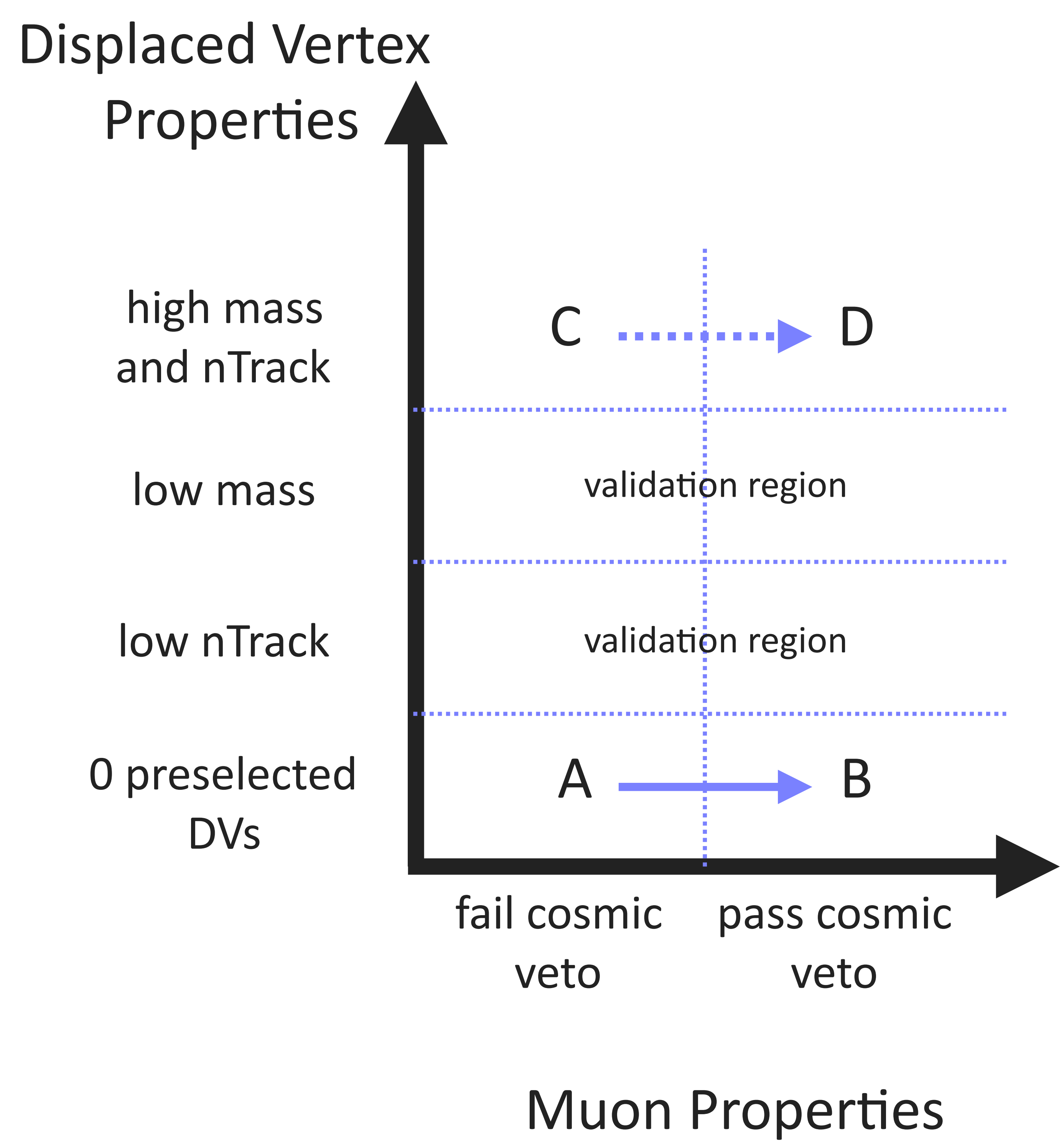
Run 2: Background Estimation Strategy

General Idea:

use both muon and displaced vertex properties of event, in "ABCD" inspired method

eg. for cosmic background at right

Very different from run 1!
Means we don't need to require DVs with ≥ 5 tracks



MET Stream backgrounds

Need to define two pure regions to measure transfer factors

impact parameter is best way to separate fakes and decays in flight

Decays in Flight

measure using muons with

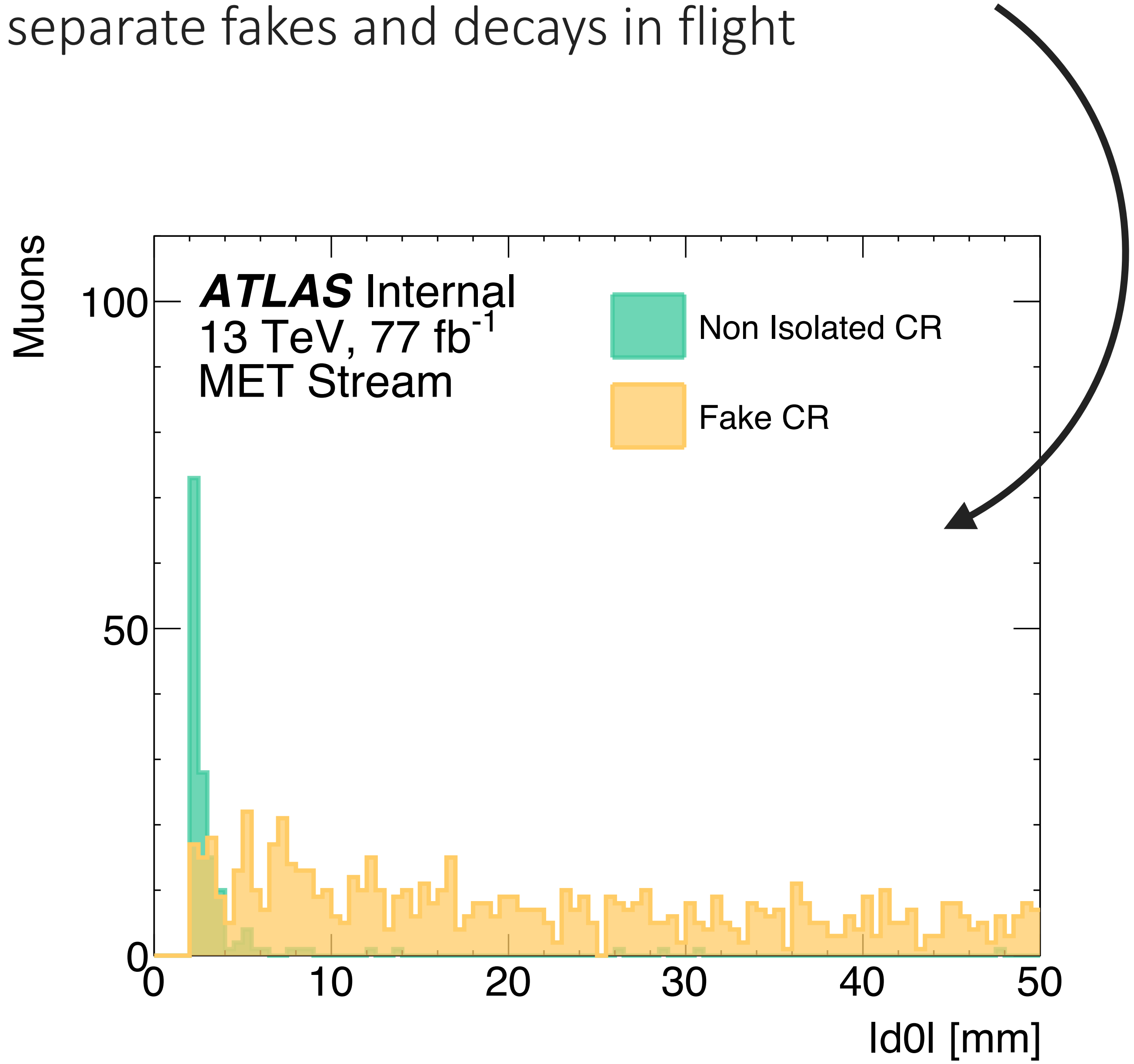
1.5 < |d0| < 2.0 mm

Fake Muons

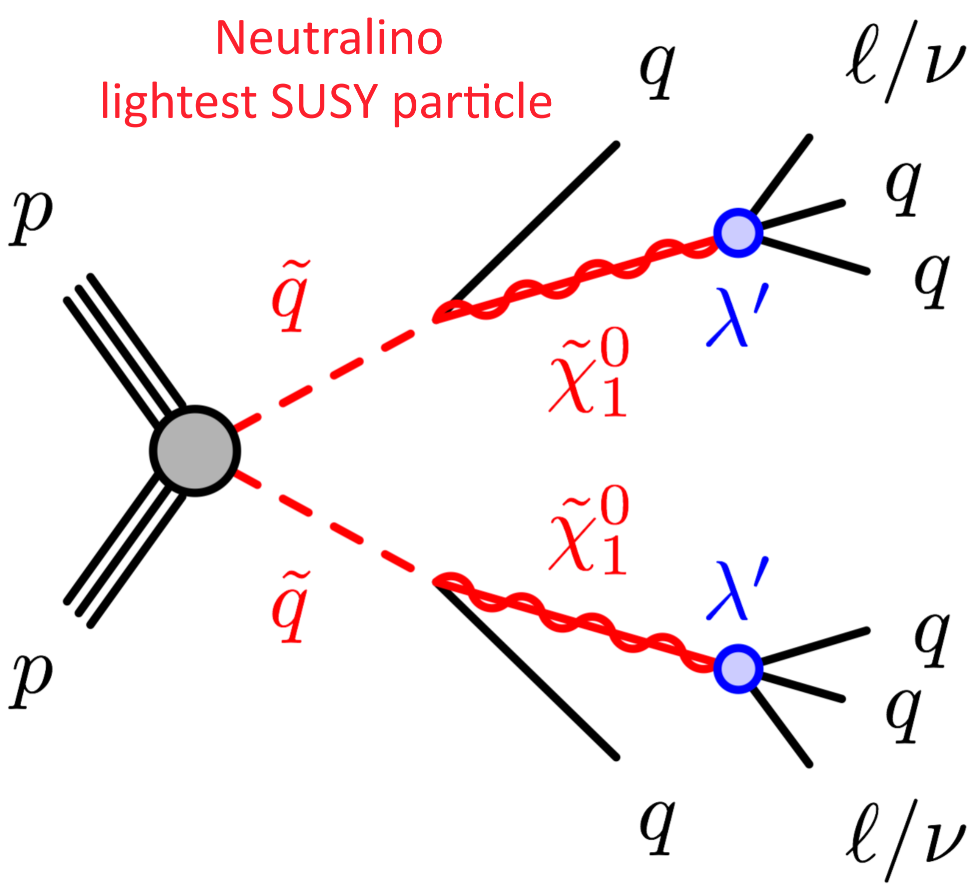
measure using muons with

|d0| > 5 mm

Challenging because we're limited by statistics for transfer factor numerators

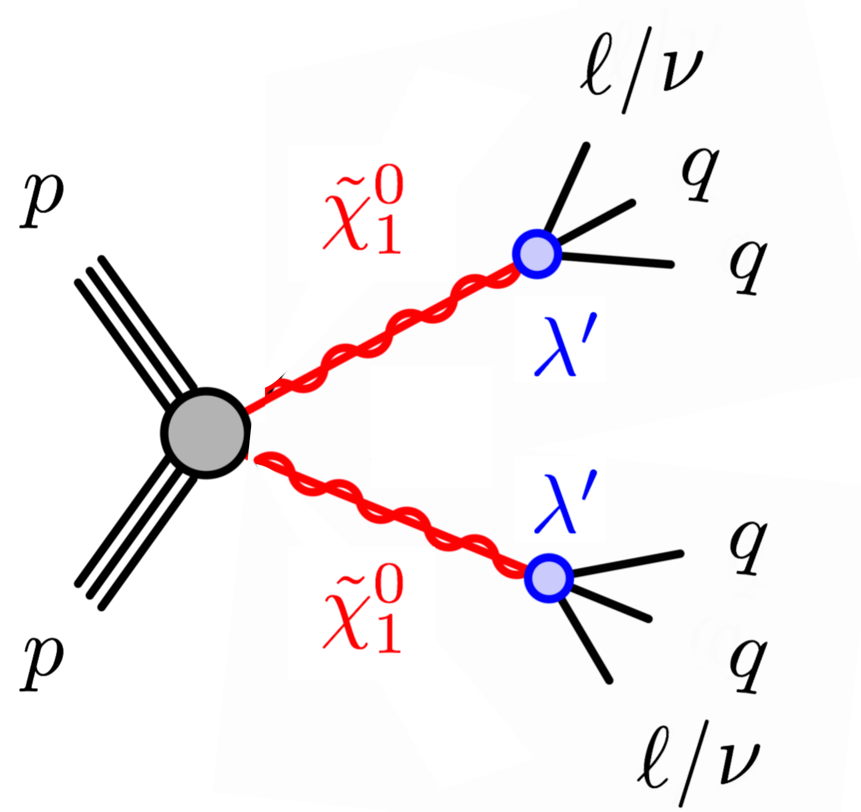


Why we kept the Muon stream



Retain sensitivity to other signals

particularly muons with lower pT

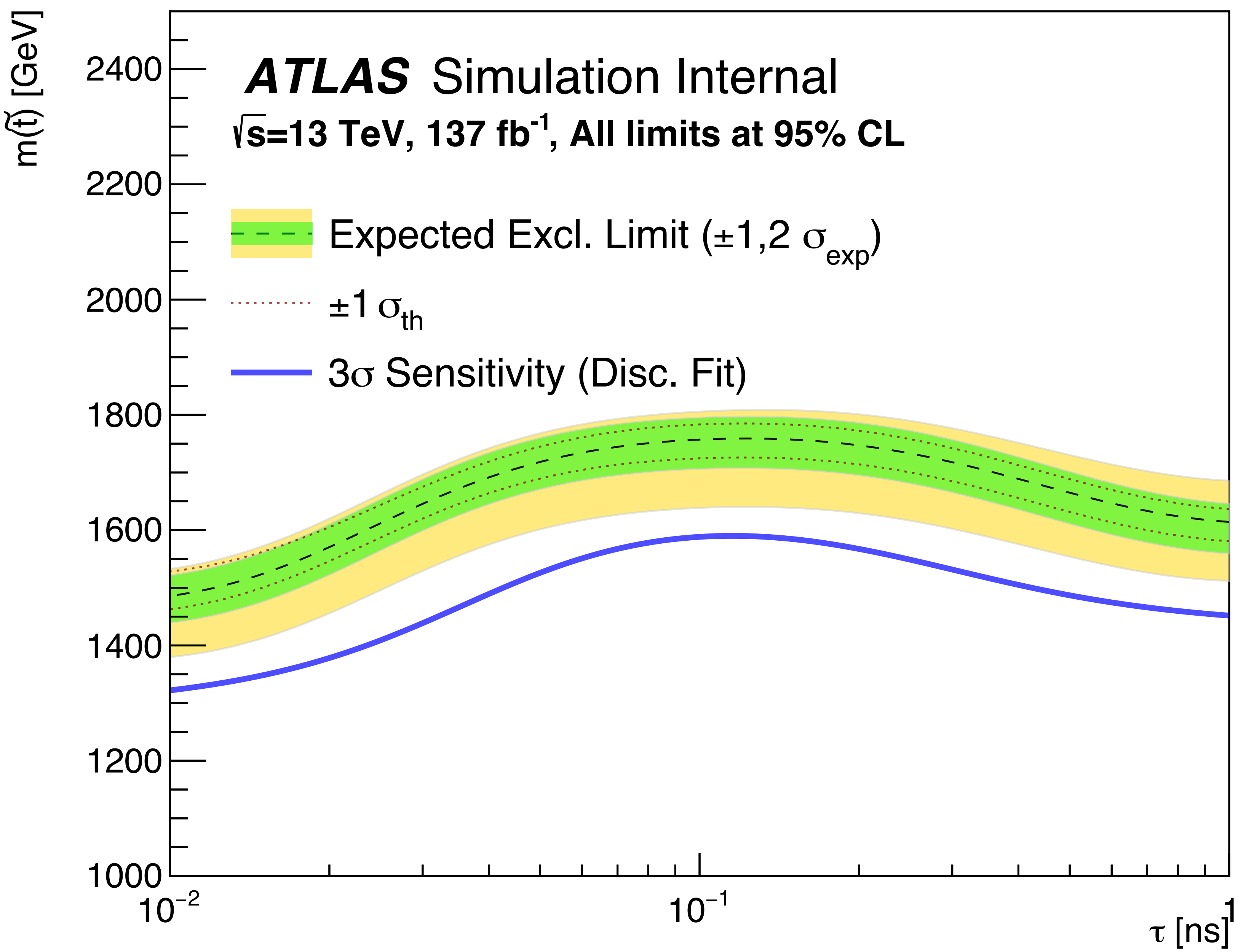


Sensitivity/Predictions

Expected sensitivity for different stop masses and lifetimes

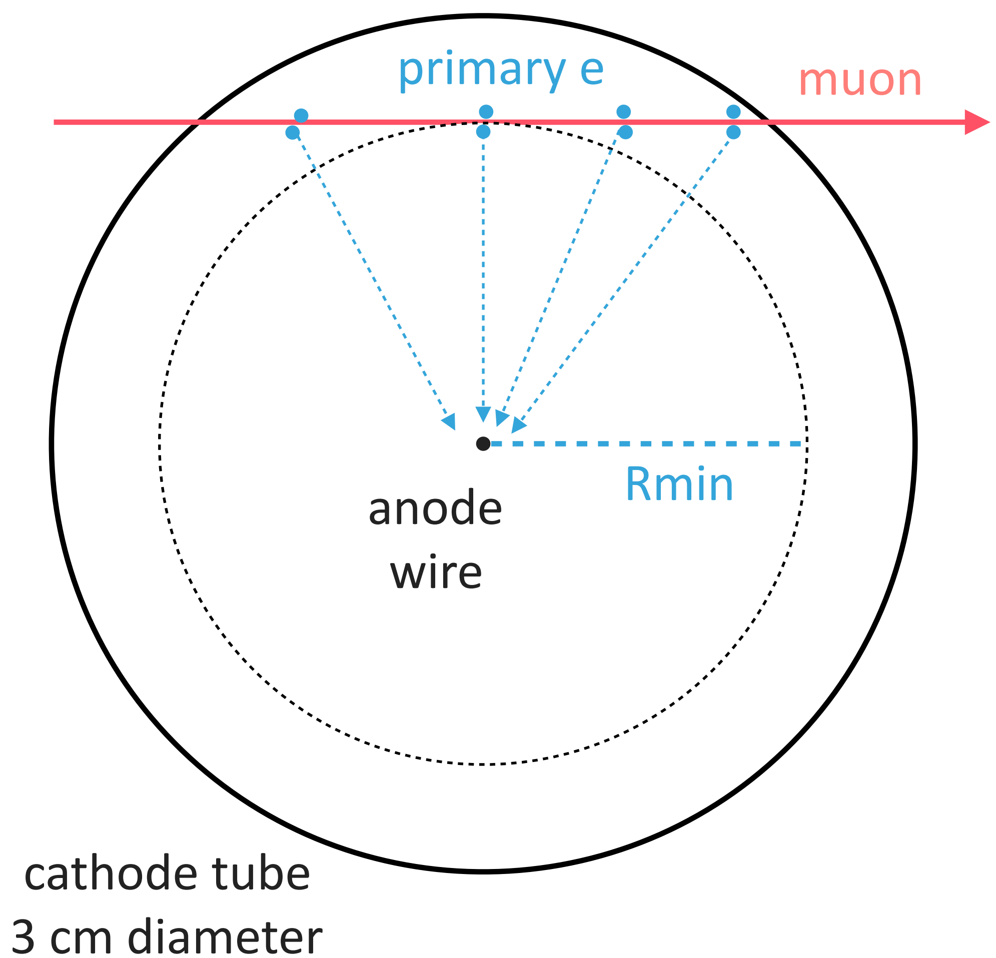
with 2016-2017 data *+2018 data*

if we scale signal and background by luminosity



Why high luminosity is challenging for the MDTs

Drift Tube Reminder



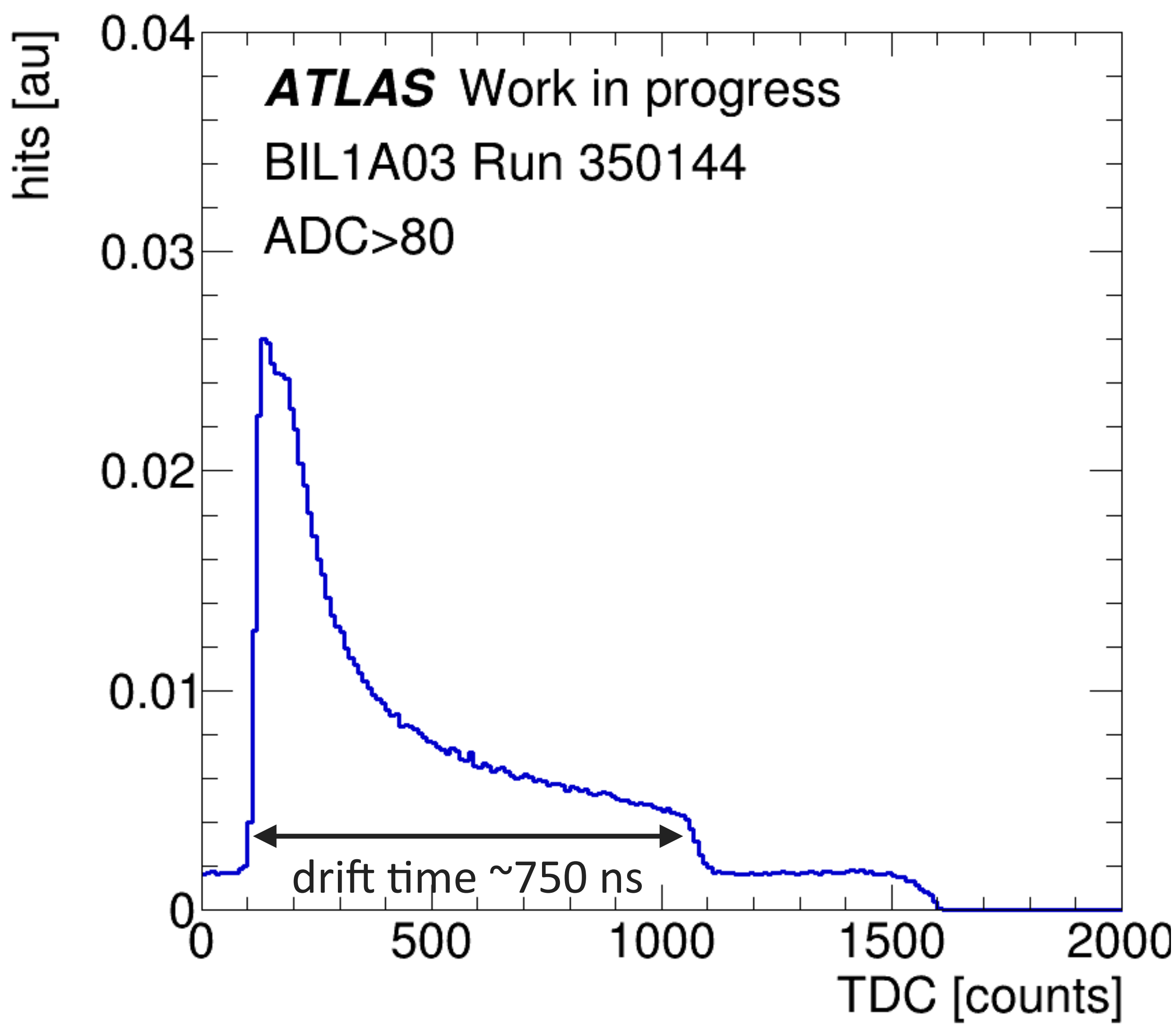
MDTs have a maximum drift time of 750 ns

dead time: if two muons pass through the same tube in <750 ns of each other you MISS the second muon

Monitored Drift Tube Timing and Charge

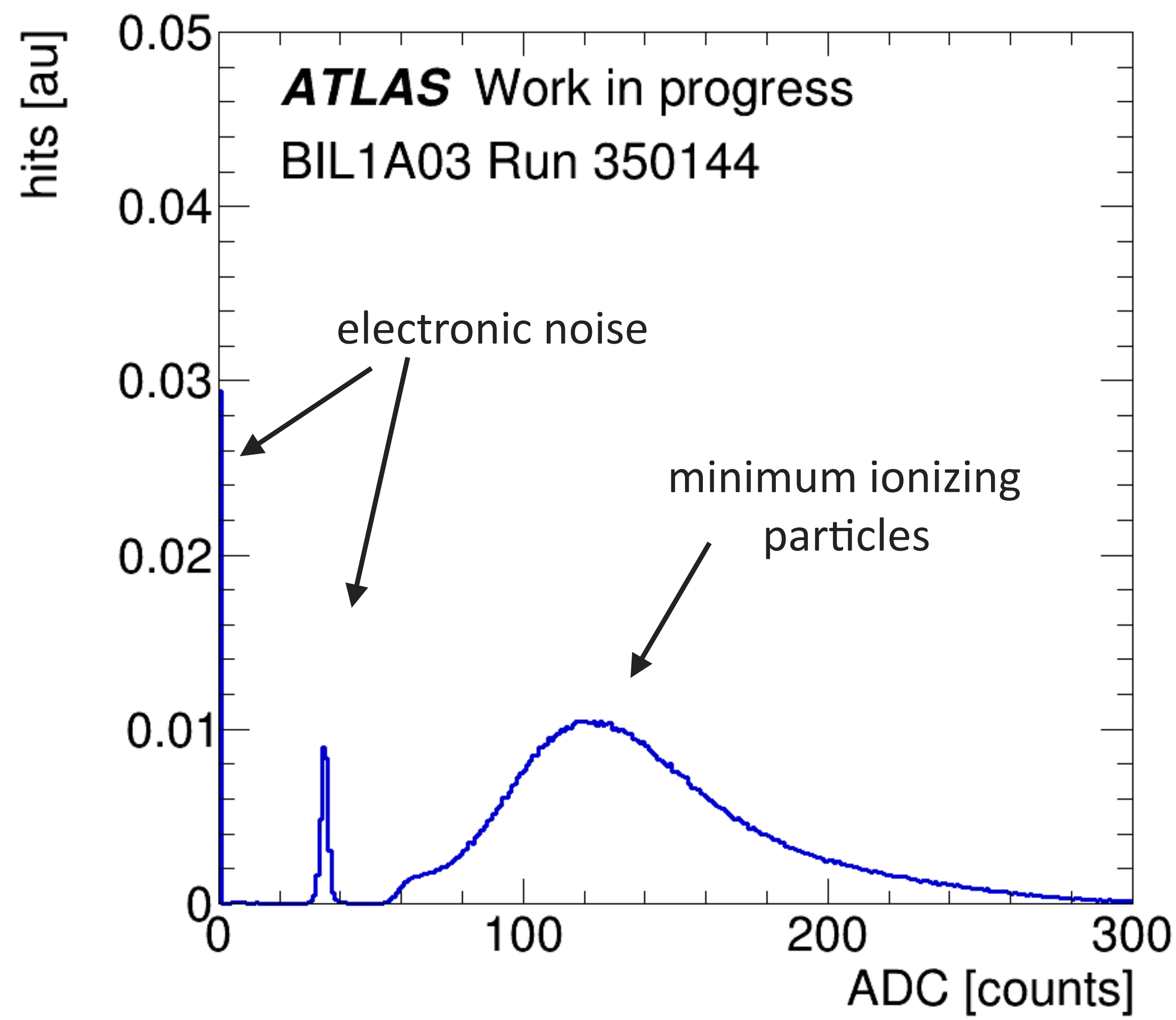
TDC = time of leading edge

~arrival time



ADC = leading edge - trailing edge

~deposited charge

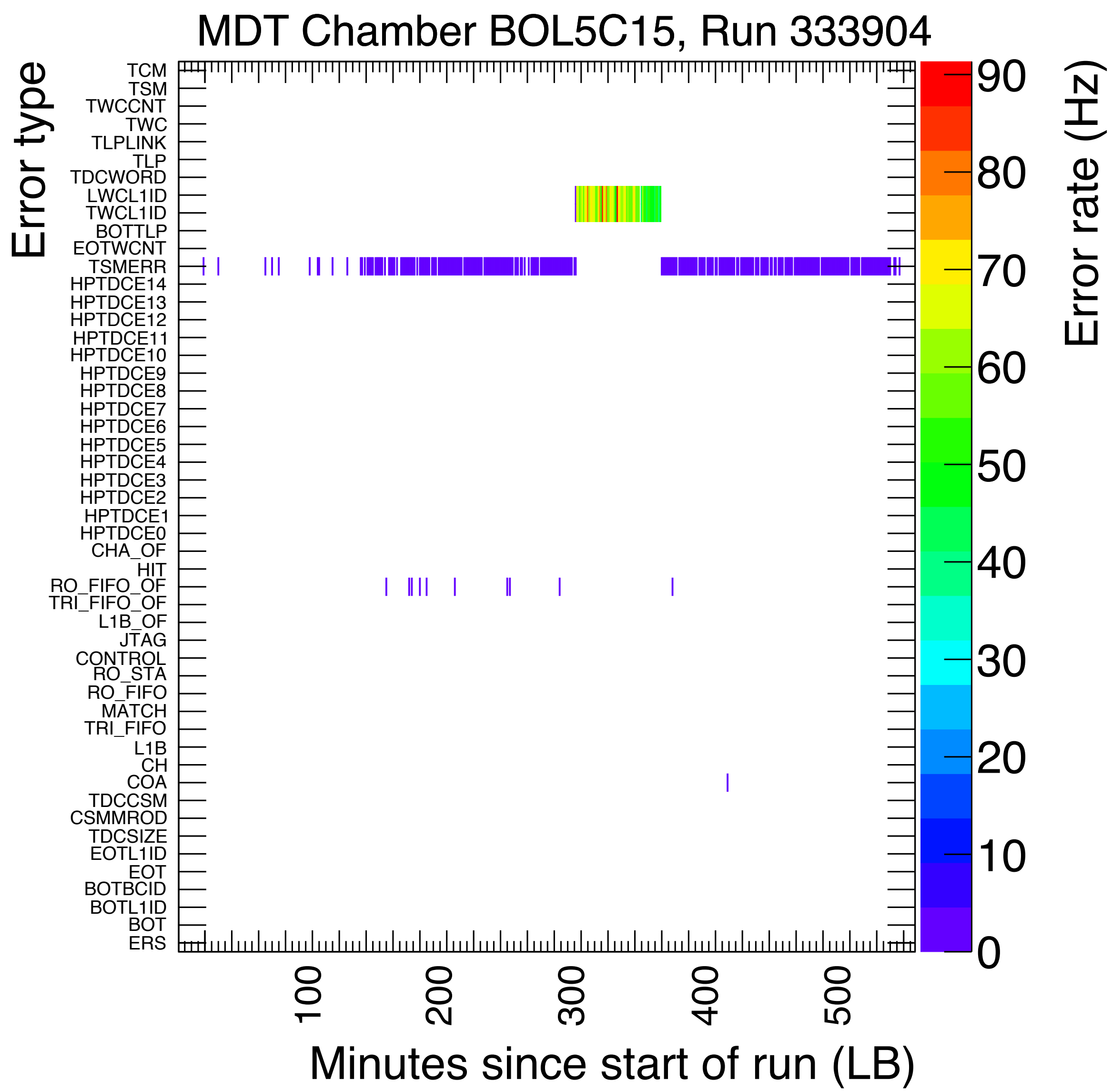


from calibration stream: hits on track and inside L1 ROIs

Monitored Drift Tubes Electronic Errors

also receive electronic error information

useful for determining when to intervene during a run



eg. TWCL1ID, LWCL1ID

MDT hits are present, but timing offset with respect to ATLAS

hits either aren't reconstructed as part of muon or we lose muon altogether

usually fixed by chamber re-initialization

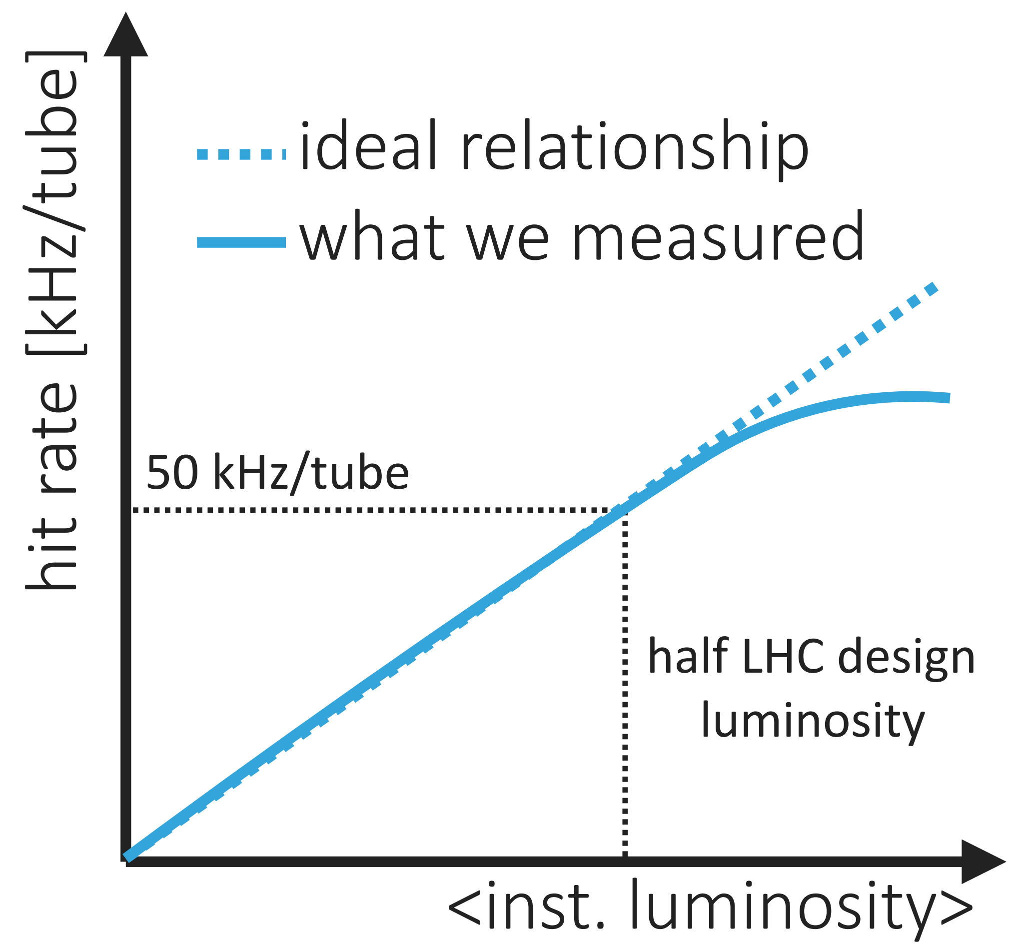
MDT Hit rates in Run 1

MDT readout saturation
in the Inner Endcap

data loss began at hit rates much lower than expected from dead time alone
~50 kHz/tube versus ~300 kHz/tube

The problem: the electronics, not the detector

Hit Rates in Inner Endcap
eta station = 1



*not a real plot!

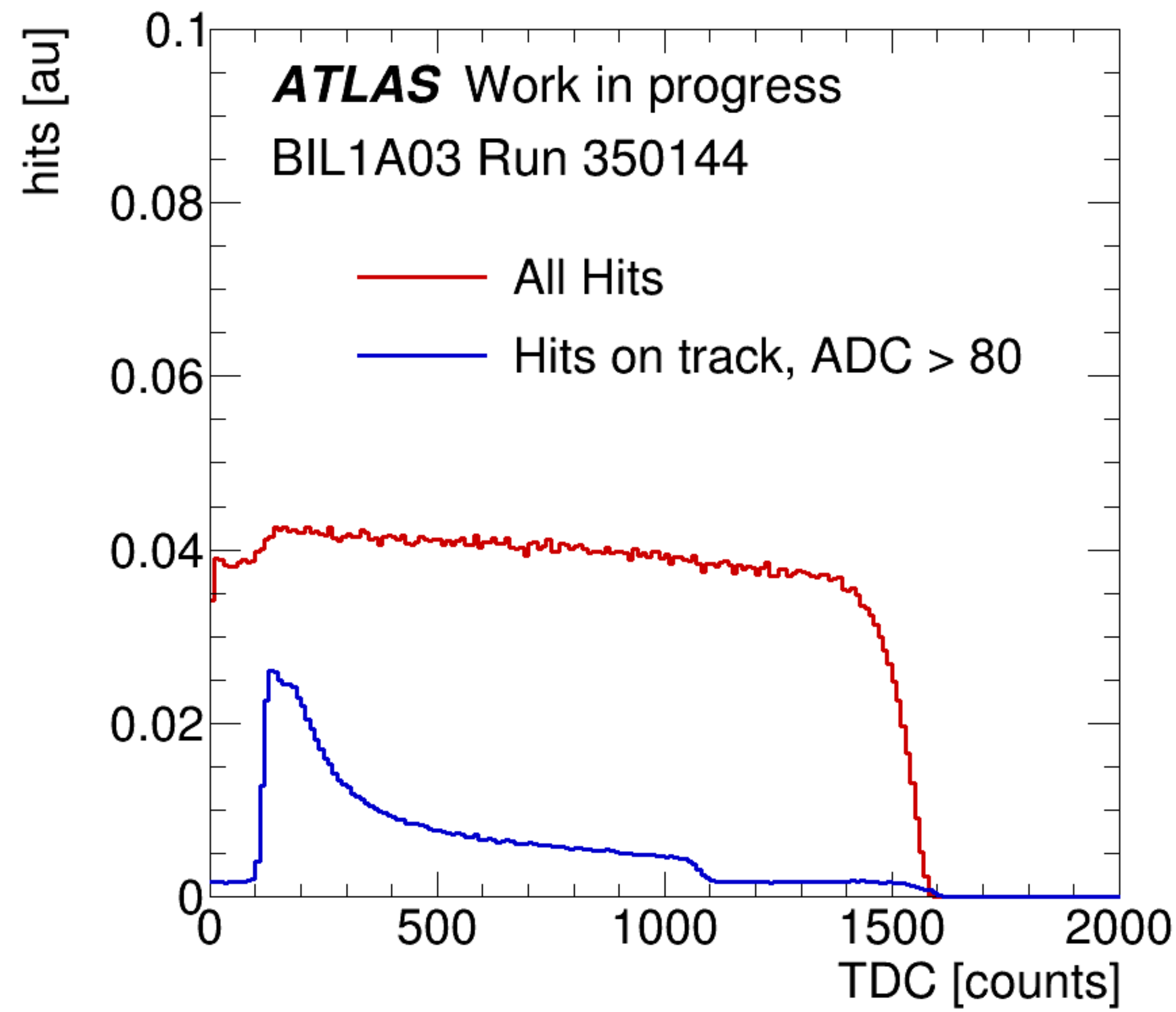
Solving Run 1 MDT Saturation

Solution 1:

Reduce MDT readout window from 2500 ns to 1300 ns

no loss of efficiency for **REAL MUONs**

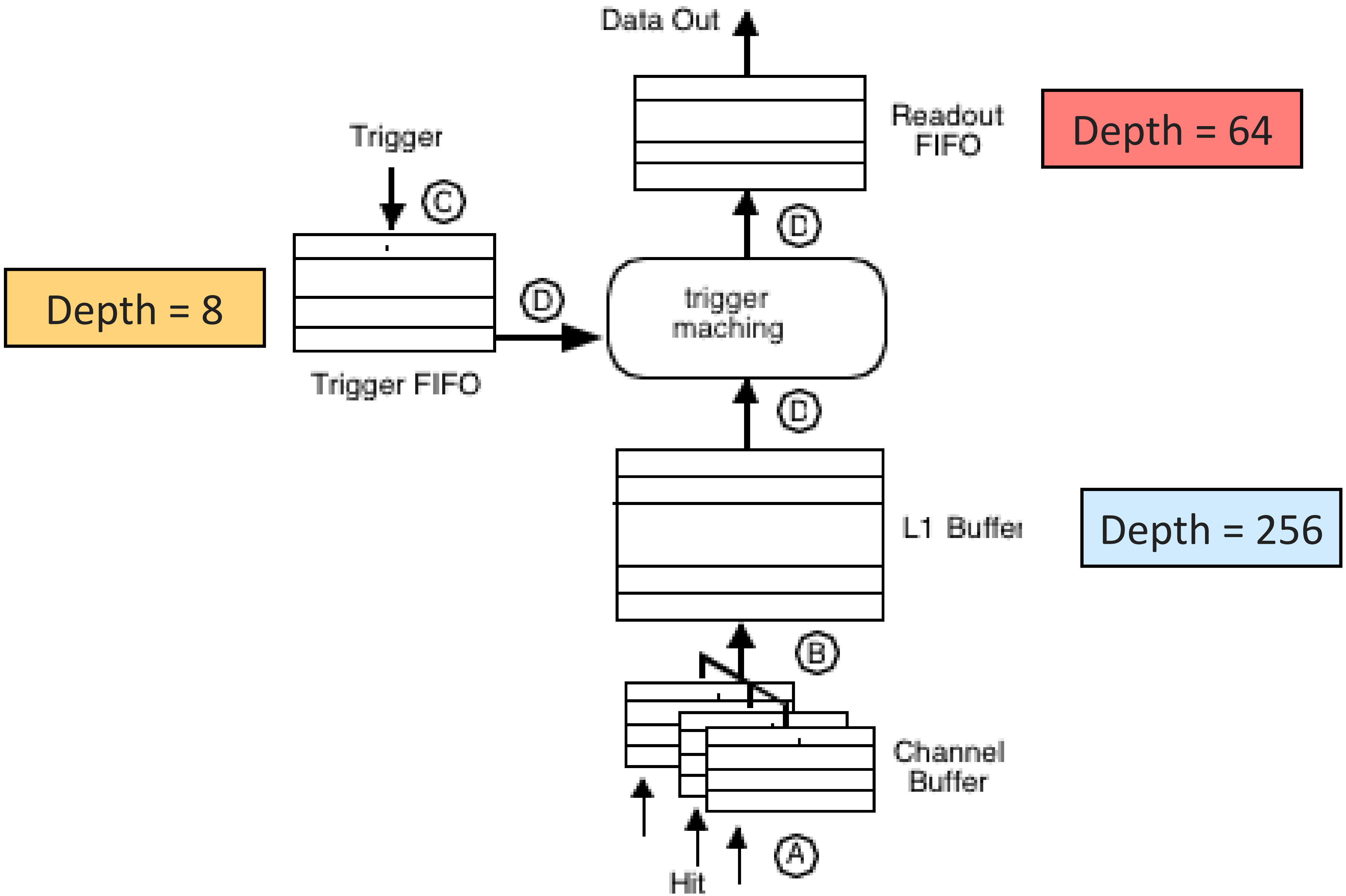
but reduces **EVENT DATA RATE** by >40%



Solution 2:

change electronics configuration, flush readout FIFOs when nearly full

MDT TDC Buffer Schemes

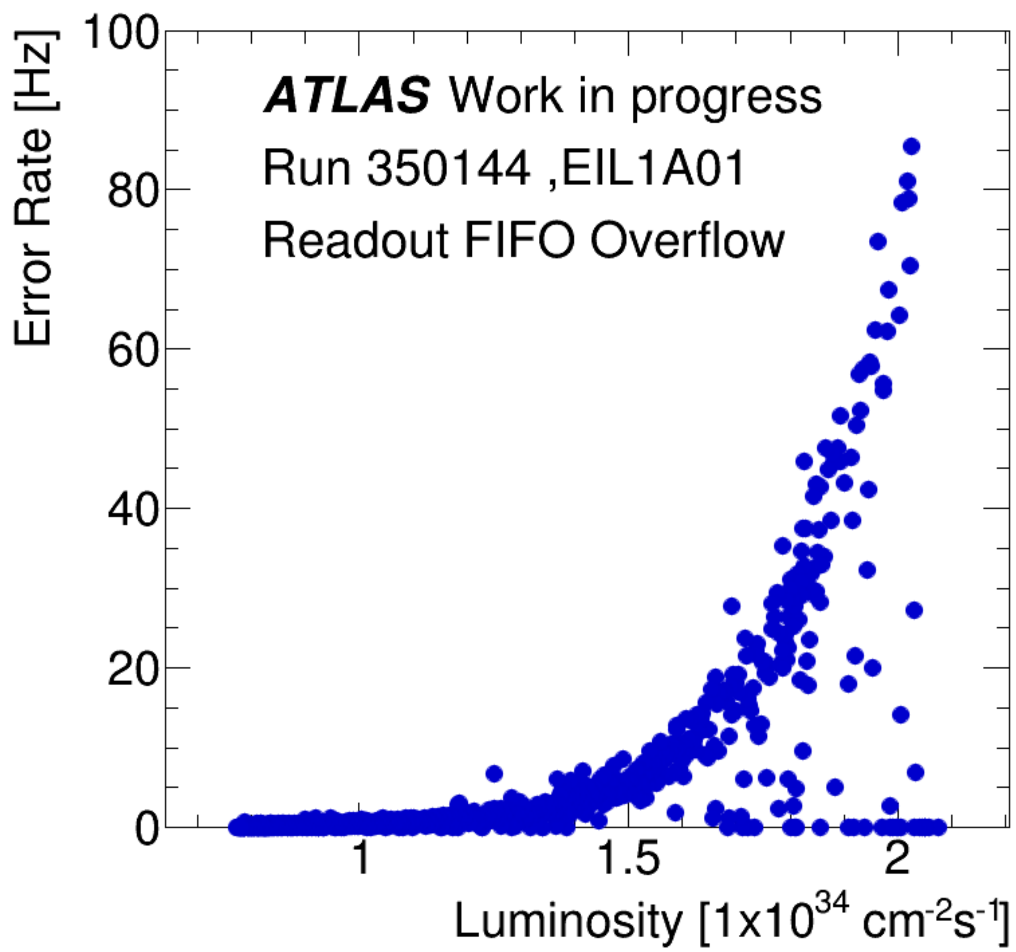


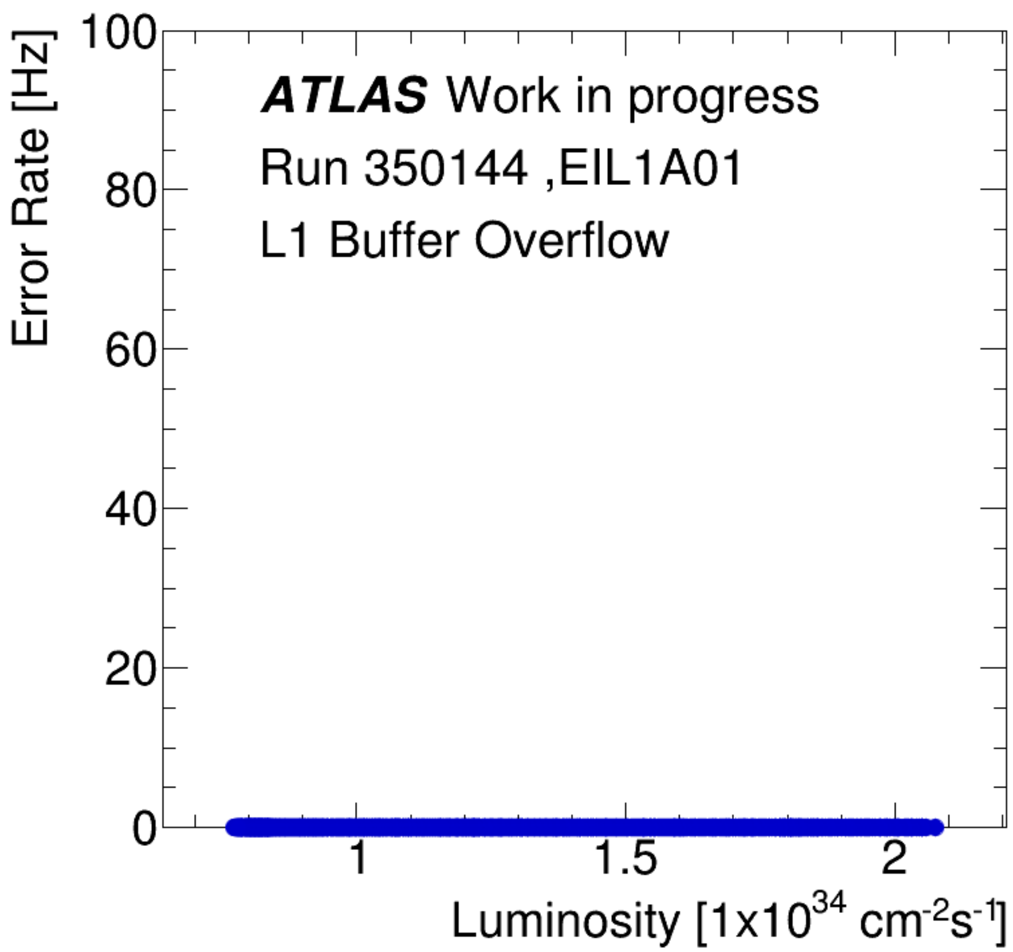
Changes in MDT electronics

Run 1 Readout FIFO would overflow, backing up hit buffers
takes long time to clear buffers
Run 2: clear readout FIFOs when nearly full,
prevent hit buffers from ever overflowing

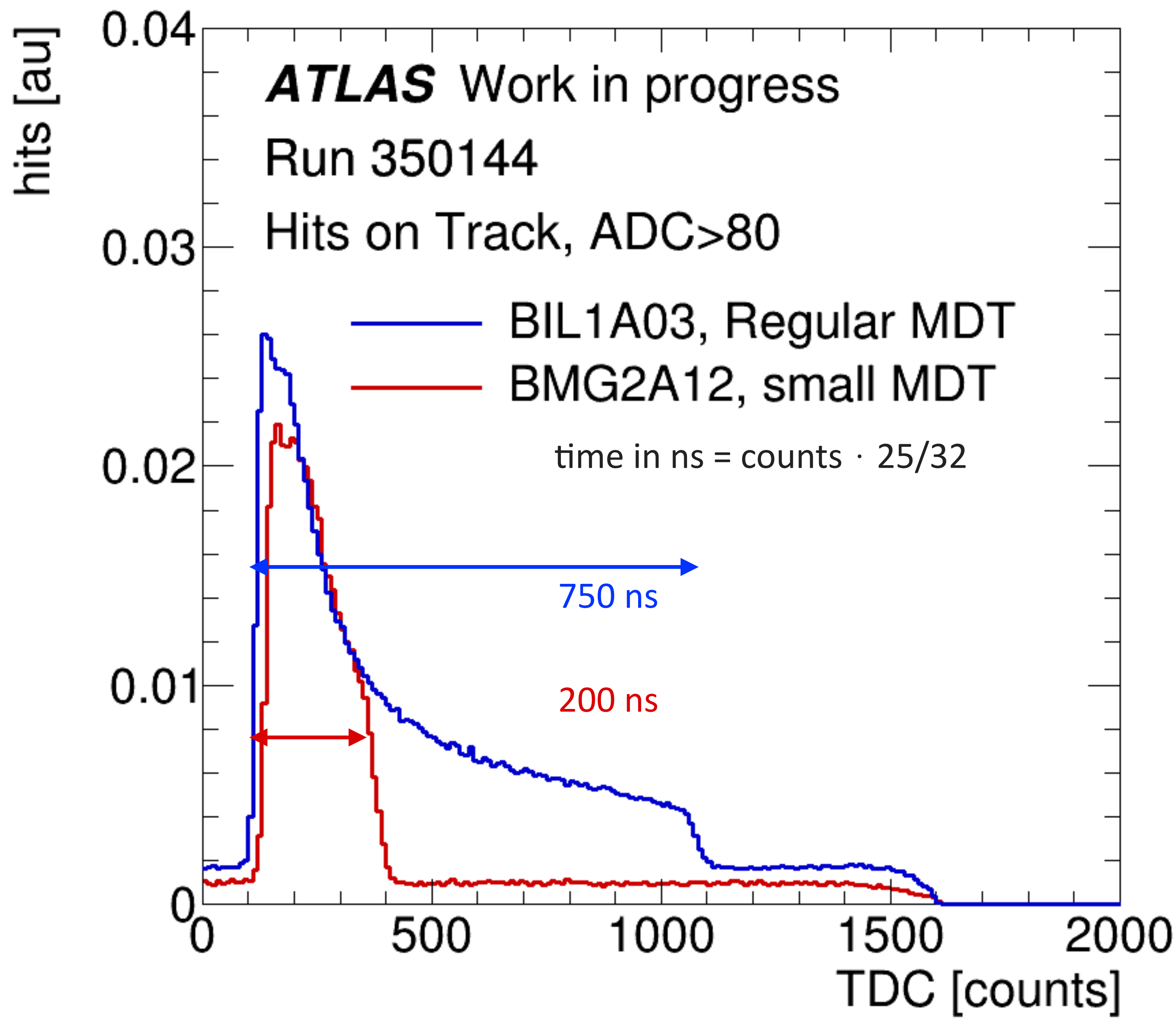
Assumptions

1. readout buffer overflow is RARE
2. clearing buffers has negligible impact on real muons





small MDT Chambers drift time



An updated hit rate model

Accounting for MDT deadtime in hit rate measurement

observed hit rate = delivered hit rate · single hit efficiency

delivered hit rate = A + $\mathscr{L}$ · B

single hit efficiency = 1 - delivered hit rate · C

gives

$$\text{observed hit rate} = (1-AC)A + (1-2AC)B\mathscr{L} - C B^2 \mathscr{L}^2$$

CSC Dead Time

140 ns dead time

5.6 mm η pitch, 13 mm ϕ pitch

1 strip = 5 mm * 1 m

Loss of hits with a rate of

~ 1 / 140 ns

~ 7 MHz / strip

~ 140 kHz/cm2

MicroMegas Boards

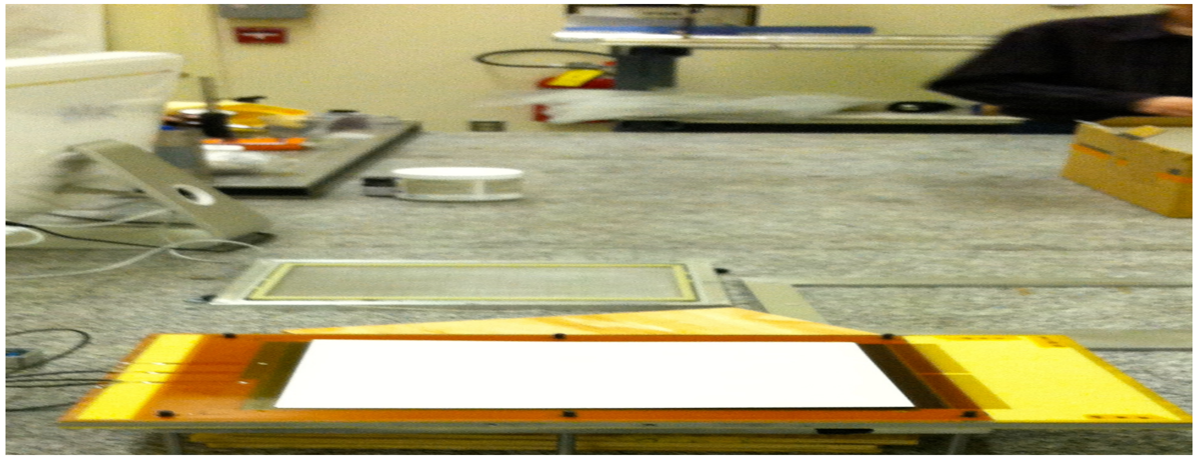
Readout Strip Design

PCBs designed at Harvard

Sent to CERN for manufacture

resistive strips, pillar, and mesh deposition

final board layout below



Testing Each Individual Board

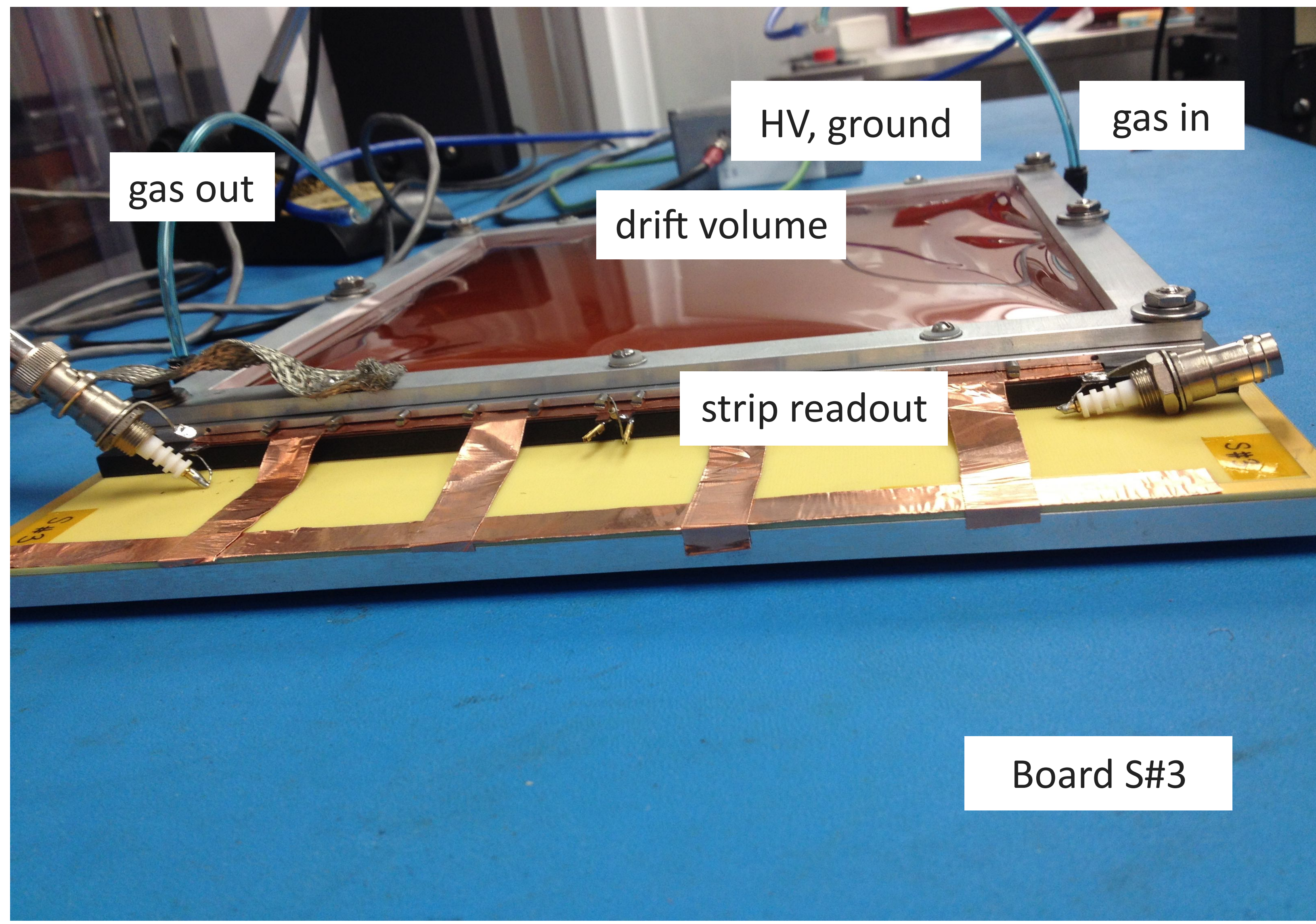
Setup for testing individual boards

Each Board tested individually before assembly

Breakdown voltage in air and in Ar:CO2

Detector Gain

Shorted Zebra connector to readout all strips at once w/ a single charge amplifier



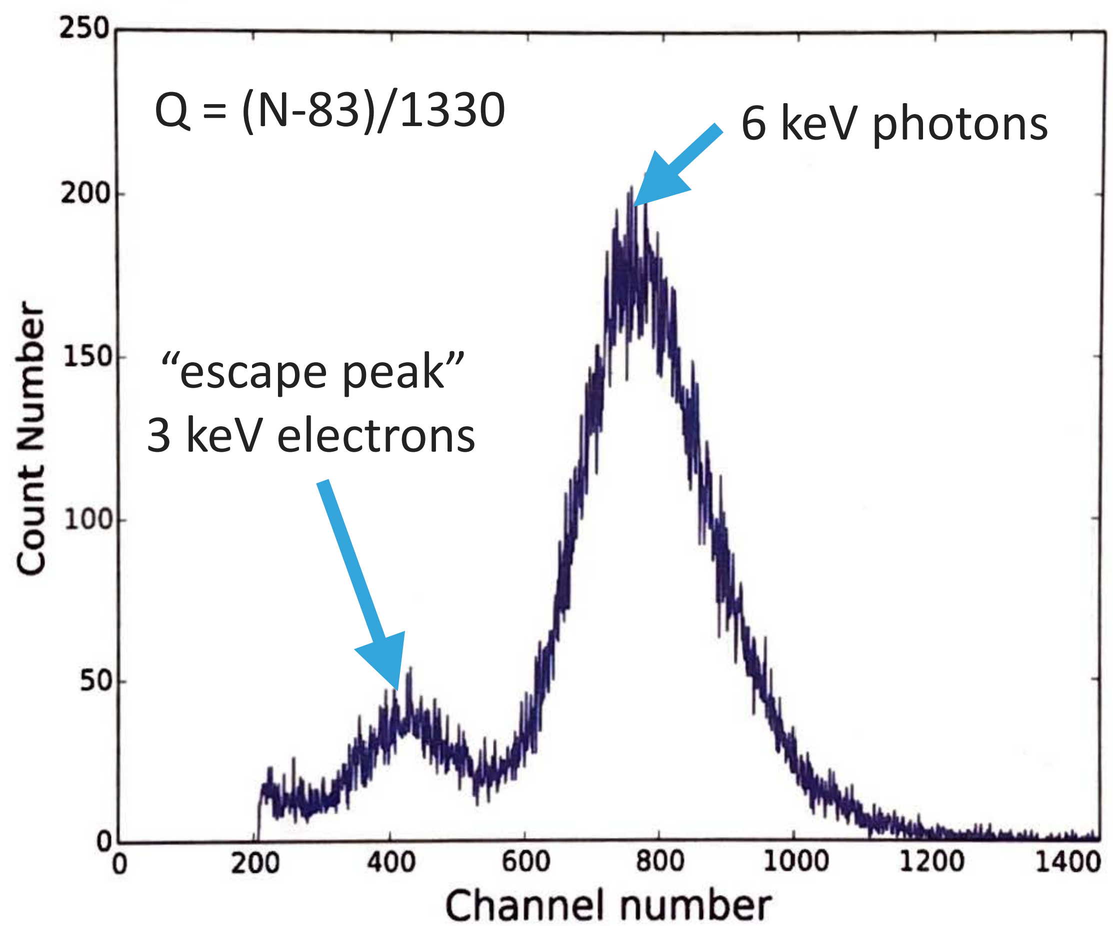
Measuring breakdown voltage in Air & Ar/CO2

define breakdown if drawing currents more than ~10 nA
or 960 V in Air
or 580 V in Ar/CO2

Board	S#1	S#2	S#3	S#4	A#1	A#2	A#3	A#4	A#5
Air	960	950	960	960	880	960	960	960	960
Ar/CO2	580	580	580	580	550	580	580	580	580

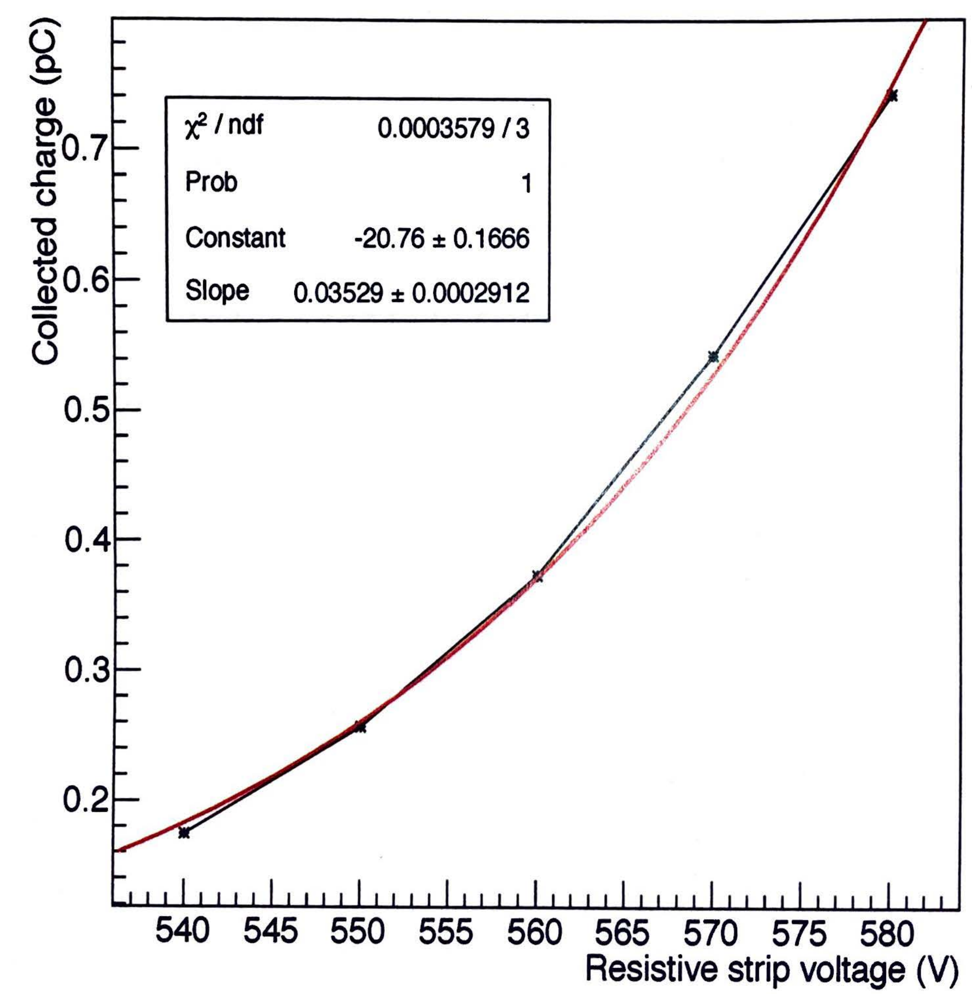
Measuring chamber gain v. strip voltage

using Fe-55 6 keV photon peak



Board S#1

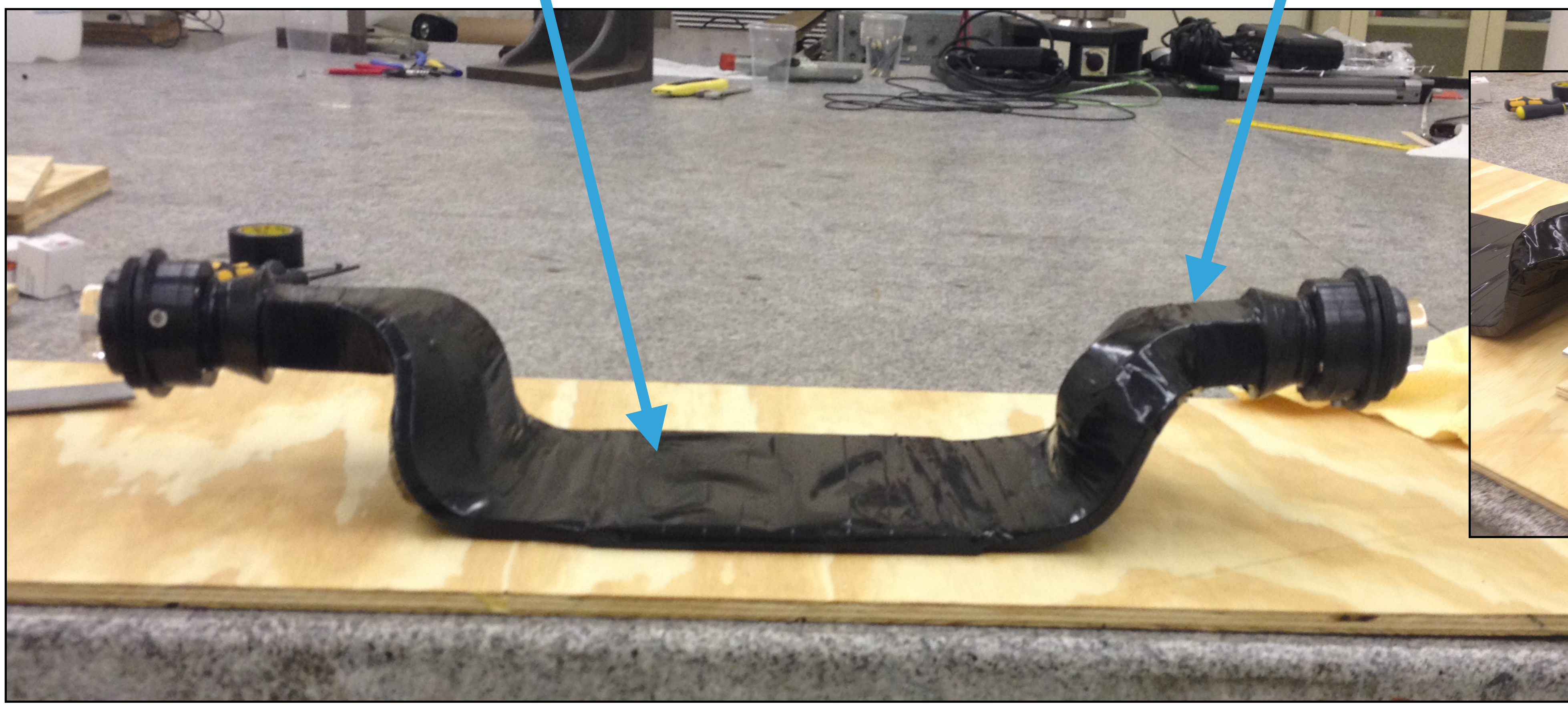
Collected Charge v. Application Voltage

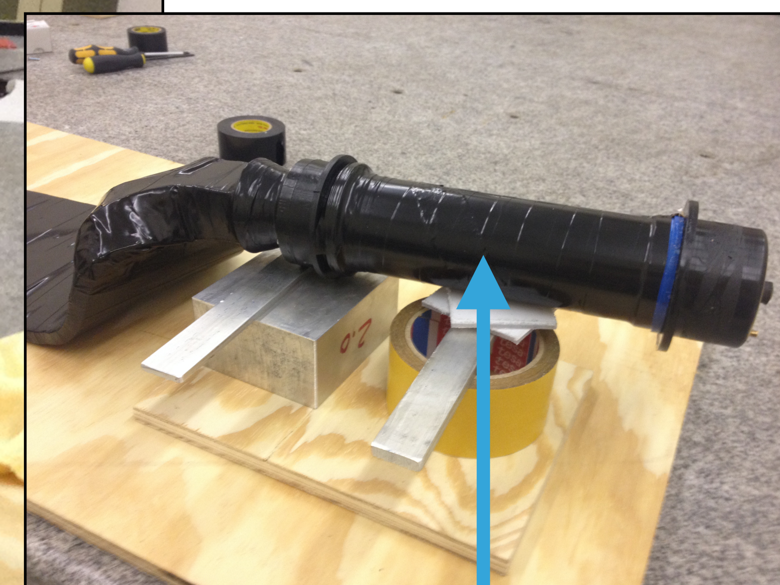


Small Trigger Counter

Scintillator
polyvinyl toluene (PVT)
+ “pop-pop” wavelength shifter

plexiglass light guides
glued to scintillator. with epoxy, and PMT
adapter with liquid plexiglass + accelerator





PMTs
recycled from CDF
hadronic calorimeter